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Freshwater inflows and the health of Galveston Bay: characterizing the nature of the nutrient and sediment loads and their effect on primary productivity.

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Table of Contents

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List of Abbreviations and Acronyms

DOM	Dissolved organic matter
cfs	cubic feet per sec
chl *a*	chlorophyll *a*
CMP	Coastal Management Program
DO	Dissolved oxygen
DOM	Dissolved organic matter
GBEP	Galveston Bay Estuary Program
GERG	Geochemical and Environmental Research Group
HB	House Bill
NOAA	National Oceanic and Atmospheric Administration
PHYTO-PAM	Phytoplankton - Pulse-amplitude-modulation Fluorometer
*rel*ETR	relative electron transport rate (μmol electrons m^{-2} s^{-1})
RLA	Resource Limitation Assay
SB	Senate Bill
TAMUG	Texas A&M University at Galveston
TCEQ	Texas Commission on Environmental Quality
TGLO	Texas General Land Office
TOC	Total organic matter
TN	Total particulate nitrogen
TP	Total particulate phosphorus
TSS	Total suspended solids
TWDB	Texas Water Development Board
USGS	United States Geological Service

1. Abstract

The Galveston Bay watershed is likely to see the largest population growth along the Texas coast in the next few decades. We need to understand how the present Galveston Bay ecosystem responds to nutrient and sediment loading from freshwater inflows in order to develop a conceptual understanding of the downstream ecological impacts of future mitigation strategies for freshwater inflows. This program addressed goals stated in the TGLO-CMP documents (Cycle 13), specifically those associated with water supply and quality. The major gap in the present knowledge continues to be a clear understanding of the downstream ecological impacts of changes to freshwater inflows and the modes of nutrient loading and the effects it has on estuaries. Herein we have examined patterns of water quality – salinity, chlorophyll, dissolved organic matter and other values – on fine spatial and temporal scales. The project spanned a range of inflow conditions into the Galveston Bay estuary between January and December 2009. Spatial maps generated from monthly sampling campaigns with a Dataflow unit provided a clear depiction of inflow effects on water quality in the system. In the fall/spring, repeated, large freshwater inflow events freshened much of the bay, introduced nutrients and lowered water clarity. Noticeable differences in the northern section (upper bay) versus the southern section (lower bay) of Galveston Bay in terms of water quality, phytoplankton biomass and community composition, much of which was related to aforementioned river inflow effects on salinity, nutrients and to a lesser degree sediment loading. The findings of this study indicate that phytoplankton communities were co-limited by N (as nitrate) and P (as orthophosphate) for much of the year and in some cases, N-limited or P-limited. In responding to nutrient additions, different components of the phytoplankton community were stimulated and the extent to their response was dependent on both the nutrient supplied and on the location in which the phytoplankton were collected, that is, northern (upper) or southern (lower) Galveston Bay. The differential responses reflect the ability of the phytoplankton in different parts of the bay to deal with perturbations in their environment which vary both in magnitude and duration. This project will contribute to the state's efforts to improve resource management by providing basic information, maps, and links to new and pre-existing data. These are all necessary for sound implementation of CMP goals and policies and updating and analysis of existing information is necessary for coastal management decisions.

Freshwater inflows and the health of Galveston Bay: characterizing the nature of the nutrient and sediment loads and their effect on primary productivity.

2. Introduction

Changes in the characteristic hydrological and physio-chemical nature of bays, basins, estuaries and bayous worldwide are occurring as a result of increased nutrient inputs (e.g., anthropogenic inputs from waste water treatment facilities and groundwater seepage) associated with urbanization and industrialization, alterations in the magnitude and frequency of freshwater inflows, changes in water circulation patterns (e.g., dredging programs for ship channels) and other human induced changes including but not limited to tourism. Of these, the most frequently investigated phenomena are eutrophication (Howarth 1988; Howarth & Marino 2006; Quigg et al. 2009a) and harmful algal blooms (Granéli & Turner 2006), which may lead to fish kills (Thronson & Quigg 2008; McInnes and Quigg 2010) and the loss of other fauna, flora, and/or habitats. Decreased water quality in Galveston Bay, Texas is no exception. Changing land use patterns, largely driven by rapid coastal development, has increased pressure to develop management strategies to protect marine flora, fauna and habitats whilst providing for human activities. To achieve this, we need to determine how Galveston Bay and other estuaries respond to environmental perturbations. We still lack a clear understanding of specific factors which are important in individual estuarine systems.

2.1 Galveston Bay

The interaction between ecosystem function and human use means that coastal zones are the most complex 'multiple use' areas in the world (Griffis and Kimball, 1996). These are also the most challenging and problematic areas in which to develop ecosystem sustainability management plans. With a rapidly expanding population in Texas coastal municipalities (TWDB 2001, 2007), regulators, managers and scientists are challenged with meeting human needs for water supply and quality, while maintaining critical freshwater inflows to estuaries. Section 11.147 (a) of the Texas Water Code and Section 501.33 Policies for Appropriations of Water define "*beneficial inflows" as those that provide a "salinity, nutrient, and sediment* *loading regime adequate to maintain an ecologically sound environment in the receiving bay and estuary system that is necessary for the maintenance of productivity of economically important and ecologically characteristic sport or commercial fish and shellfish species and estuarine life upon which such fish and shellfish are dependent*". Galveston Bay, also referred to as the Trinity-San Jacinto Estuary, is in the largest watershed on the Texas coast (see Thronson and Quigg, 2008 for details). It faces some of the greatest conservation challenges of any system in Texas given that it is adjacent to the most populated and industrialized area of the state. The 24,000 square mile (62,000 square kilometer) Galveston Bay watershed dwarfs the 600 square miles covered by the bay's open waters (www.gbep.state.tx.us). It reaches as far north as the Dallas-Fort Worth area, draining to the Trinity River which, in turn, ultimately flows to Galveston Bay. Due to the large aerial coverage and presence of the urbanized areas within the watershed, approximately half the population of the state of Texas lives within its boundaries and has a large potential impact on the estuary.

The "lower" Galveston Bay watershed is defined as the 4,000 square mile (10,000 square kilometer) area draining to the Bay downstream of two major impoundments: Lake Houston on the San Jacinto River, and Lake Livingston on the Trinity River. Due to attenuation provided by the two reservoirs, the lower watershed more directly contributes pollutant loadings to the Galveston Bay system than does the "upper" Galveston Bay watershed (www.gbep.state.tx.us). Upper Galveston Bay receives the outflow of the San Jacinto River and much of the local drainage from the City of Houston via the Houston Ship Channel. Trinity Bay receives the outflow from the Trinity River. It is within this lower watershed that this research program focuses its efforts.

The Galveston Bay system is adjacent to one of the most urbanized and industrialized areas in Texas and the nation. Four million people resided in the five counties (Brazoria, Chambers, Galveston, Harris and Liberty) surrounding Galveston Bay in 2000, making Houston the 4th largest metropolitan area behind New York, Los Angeles, and Chicago (U.S. Census Bureau, 2001). Harris County is the most populous in the state of Texas with 3.4 million people in residence in 2000. That is an average of 1,967 persons per square mile! This number is NOW likely to be greater but at the time of writing this report the 2010 Census results were not yet available. Suburban and industrial development are reducing critical wetland habitat at a faster rate than anywhere else along the coast (www.gbep.state.tx.us). The majority of Texas' hazardous chemical spills and the largest oil spills occur in this system (www.gbic.tamug.edu). In an investigation of fish kills occurring along the Texas coast from 1951 to 2006, Thronson and Quigg (2008) found that Galveston and Matagorda Bays had the highest number of fish kill events and total number of fish killed.

Given Galveston Bay is predicted to experience the largest population growth of any of the Texas coastal municipalities in decades to come (TWDB 2007), it is imperative that we understand how it responds to freshwater inflows – total discharge, pulses of differing magnitude, circulation patterns and/or returned flows – resulting from alterations in its watershed. We need to understand how the present Galveston Bay ecosystem complex responds to nutrient and sediment loading from freshwater inflows in order to develop a conceptual understanding of the downstream ecological impacts of future mitigation strategies for freshwater inflows and modes of nutrient loading into this system. Specifically, how do changes in nutrient and sediment loading effect primary productivity and phytoplankton community composition? If the basis of the food web is altered, the impact will be transmitted to all higher trophic levels.

2.2 House Bill (HB) 3 and Senate Bill (SB) 3

Created by the 80th Texas Legislature, 2007, in recognition of the importance that the ecological soundness of our riverine, bay, and estuary systems and riparian lands has on the economy, health, and well-being of our state, House Bill (HB) 3 and Senate Bill (SB) 3, requires the Texas Commission on Environmental Quality (TCEQ) to adopt, by rule, appropriate environmental flow standards for each river basin and bay system in the state. Senate Bill 3 begins the implementation of the state's 50-year water plan. Details of the process can be found at: http://www.tceq.state.tx.us/permitting/water_supply/water_rights/eflows/group.html.

The adoption schedule, as amended, requires environmental flow standards for the river and bay systems consisting of the Sabine and Neches Rivers and Sabine Lake Bay, and the Trinity and San Jacinto Rivers and Galveston Bay to be adopted by June 1, 2011. To comply with HB 3/SB 3, TCEQ staff is proposing the creation of new 30 Texas Administrative Code Chapter 298, Environmental Flows, Subchapter A, Sabine and Neches Rivers and Sabine Lake Bay; and Subchapter B, Trinity and San Jacinto Rivers and Galveston Bay.

SB 3 empowers the TCEQ to set aside fresh water to inflow into the state's bays and estuaries in an effort to maintain the health of inter-coastal waterways. The science behind this flow management is being developed by a Texas Environmental Flows Science Advisory Committee, made up by hydrologists and other earth-scientists who advise TCEQ on the best way to ensure the viability of bays and estuaries. This plan would be suspended in the event of a natural emergency, like a drought, where water resources would be diverted to help human services. The Texas Water Development Board (TWDB) would be directed to create a state-wide conservation awareness program under SB 3.

SB 3 will also help Texas implement a consistent water management plan across the state by adding more oversight to local water policies. Final decisions for water management will still lie at the local level, but SB 3 will require groundwater conservation districts to submit comprehensive management plans to TWDB for comment. SB 3 will also create groundwater management area councils to advise local water management boards. All unincorporated publicly owned land will be administered by a state groundwater conservation district. SB 3 will also require water vendors to report water sales in an effort to determine actual water usage in Texas.

This is the first time in the state's history that the state's obligation to set aside a volume of water for the protection of the environment has been recognized. SB 3 contains “environmental flows” provisions that will move Texas towards setting aside water for fish and wildlife, while still meeting human water needs and protecting existing water rights of cities, agriculture and industry. SB 3 is a major step towards ensuring that future generations of Texans have flowing, healthy rivers and productive bays, estuaries and fisheries. Done properly, SB3 means Texas will lead the way in showing how water resources can be managed rationally.

2.3 Major findings of previous and ongoing studies

This program builds on earlier TGLO-CMP projects. As part of Cycle 10, the focus of efforts was on “Changes in Freshwater Inflows and How They Effect Texas Bays” (Quigg et al. 2007). The project spanned a range of inflow conditions into the Galveston Bay estuary between

January and December 2006. Spatial maps generated from monthly sampling campaigns with a Dataflow unit provided a depiction of inflow effects on water quality in the system. In the fall and spring, repeated inflows events freshened much of the bay, introduced nutrients and lowered water clarity. Fixed station data supported this, particularly with regard to inorganic nutrient (N and P) concentrations. The findings of this study suggested that the upper bay was likely limited by the availability of N (based on atomic ratios of N:P) and this may be enhanced by inflow events. Primary productivity was mapped on fine spatial scales for the first time with a PHYTO-PAM. Higher phytoplankton biomass (measured as chlorophyll concentration) did not always correspond to higher productivity. A physiological examination of the phytoplankton revealed that they were stressed by some environment factor, most likely to be light or nutrients or a combination of these two factors. Spatial maps of Cyanophyta and Dinophyta plus Bacillariophyta (diatom) distributions reveal distinctive patterns which may be related to freshwater inflows, but also to bay wide circulation patterns and other physical processes. Noticeable differences in the northern section (upper bay) versus the southern section (lower bay) of Galveston Bay in terms of water quality, primary productivity and community composition, was related to aforementioned river inflow effects on salinity and inorganic nutrients.

Subsequently, “The impact of changing freshwater inflows on the health of Galveston Bay” (Quigg et al. 2009b) allowed additional monitoring of water quality, primary productivity and phytoplankton community composition in response to freshwater inflows to the Galveston Bay estuary (Cycle 12, TGLO-CMP). This program enabled us to begin a new baseline in January 2008 and collect much valuable data that has been subsequently used to refine new research programs and focus questions. The focus was shifted to examine specifically the effect of nutrient and sediment loads as a component of freshwater inflows to Galveston Bay. These loads introduce nutrients (N, P, Si, organic matter, various pollutants) and reduce water transparency (sediment loading). At the base of the food web, primary producers are the most sensitive to such changes in water quality. By monitoring the response of primary producers in Galveston Bay to nutrient and sediment loading, Cycle 12 funding enabled us to determine that phytoplankton were co-limited by N (as nitrate) and P (as orthophosphate) for much of the year (Quigg et al. 2009b). Further, phytoplankton were not found to be light limited.

More importantly, this program was important in allowing us to secure additional funds and expand the scope of the program. This includes support in grants from:

(i) TCEQ through the Galveston Bay Estuary Program (GBEP) Office,
(ii) TWDB through the Bays and Estuaries Program Surface Water Resources group,
(iii) Texas Sea Grant and
(iv) This new grant from TGLO-CMP.

In combination, our group has focused on Galveston Bay with the specific aim of developing process based understandings of the downstream ecological impacts of changing freshwater inflows. Specifically, we have performed high resolution spatial and temporal mapping of water quality parameters (e.g., salinity, temperature, chlorophyll) on monthly time scales from June 2005 to November 2006 (Davis et al. 2007) and January 2008 to September 2010 (Quigg et al., 2007, 2009b). We also have basic nutrient, primary productivity, phytoplankton community analyses and respiration data for fixed stations in Galveston Bay (Quigg et al. 2009b). This research needs to continue in order to build up an understanding of how the bay responds to natural variations. This research is timely given the discussions associated with Senate Bill 3 and the major gaps in understanding identified by the Galveston Bay Expert Science Team (Espey et al. 2009).

2.4 Nutrient and sediment loading to Galveston Bay

The degree of nutrient and sediment loading are important factors contributing to water quality and ecosystem health in estuaries (Longley, 1994; Nixon 1995). In 1999, Guillen published a report indicating that primary production in Galveston Bay was phosphorus (P) limited while more recently Örnólfsdóttir et al. (2004) and Quigg et al. (2009b) reported that it was nitrogen (N) limited. The latter report also found evidence of co-limitation of productivity by both N and P. Given that primary productivity is light driven, and that sediment loads decrease water clarity, the interaction between these this components of freshwater inflows clearly needs to be addressed. Sediment loading into Galveston Bay would be predominately from the two main river sources: San Jacinto River (northwest) and Trinity River (northeast). Given that Galveston Bay is relatively shallow, wind driven mixing would also play an important role in maintaining particulates in the water column and/or benthic re-suspension. Less is known about the role of sediment loading in regulating primary producers in estuarine systems.

In a recent study conducted in Moreton Bay, a subtropical estuary in Queensland, Australia, it was found that the response of the phytoplankton community was determined by location of sampling stations in the Bay. Quigg et al. (2010) found that phytoplankton communities were light-limited in the rivers leading into the Bay and at the mouths of the rivers while phytoplankton communities on the ocean-side of the Bay were typically nutrient (N as nitrate and/or N as ammonium) limited. As with Galveston Bay, major concerns for the health of this ecosystem have arisen due to increased urbanization. Quigg et al. (2010) found a gradient of responses from land-side to ocean-side directly reflecting increased nutrient and sediment loading to relatively pristine conditions respectively. A similar such gradient may also exist in Galveston Bay, but appear more as riverine-side in the north (Trinity and San Jacinto River basins) to ocean-side in the south at the inlet at Boliver Pass which allows exchange with water from the Gulf of Mexico. This is worthy of further investigation. Factors equally important, but not often addressed, include the magnitude of flushing and nutrient loading, the mode of nutrient loading, and the ratios of potentially limiting nutrients within the load (Malone et al, 1988; Chan and Hamilton, 2001)

2.5 Objectives

The main objective of this program was to support continued research aimed at determining the effect of nutrient and sediment loads, both components of freshwater inflow, on primary productivity and the phytoplankton community in Galveston Bay. Building on data collection efforts underway with the support of several agencies - Texas Water Development Board (TWDB), Texas Sea Grant and the Galveston Bay Estuary Program (GBEP) - this study will address the following specific objectives:

(i) High spatial and temporal resolution mapping of Galveston Bay, and
(ii) Characterize nutrient and sediment load effect on primary productivity.

While it is known that freshwater inflows bring with them nutrient and sediment loads, the nature of these inputs is dependent on a number of variables including but not limited to the volume and magnitude of the freshwater inflow, the source (Trinity versus San Jacinto), and the season. We will examine the composition of nutrient (nitrate, nitrite, ammonia, urea, phosphate, silicate) and sediment (total suspended load, total dissolved load, total organic carbon, turbidity, particle size distribution) loads into Galveston Bay from Trinity and San Jacinto rivers during a dry period (summer months) and after a number of freshwater inflow events (fall and spring months). These have two potential impacts on the primary producers:

(i) the addition of nutrients will stimulate phytoplankton growth and, may lead to algal blooms and/or shifts in community composition, and
(ii) the decreased light availability from excess sediments, lowering production, and/or biodiversity of the community.

We will test the influence of nutrient and sediment load by performing a series of "resource limitations assays" (RLAs)

3. Methods

Real-time flow data from a USGS monitoring station (Trinity River at Romayor 08066500) near the river's mouth was used to determine the freshwater inflow into Galveston Bay from January to December 2009.

3.1 Water Quality Mapping

The Dataflow, a high-speed, flow-through measurement apparatus developed for mapping physio-chemical parameters in shallow aquatic systems (Madden and Day 1992), was used to map along a tightly gridded transect, Galveston Bay (Fig. 1). This integrated instrument system concurrently measured water temperature, conductivity, salinity, water clarity (beam transmittance), chlorophyll *a* (*in situ* fluorescence), and dissolved organic matter (DOM; *in situ* fluorescence). Water quality measurements were taken at 4-sec intervals (every 2–8 m depending on boat speed) from about 10 cm below the surface. An integrated GPS was used to simultaneously plot sample positions, allowing geo-referencing of all measurements for each variable. Water quality surveys took two successive days in Galveston Bay. GPS and Dataflow information was used to create highly detailed contour maps of water quality parameters in relation to physiographic features using Surfer. Discrete water samples were collected from six fixed stations (Fig. 1) for laboratory analysis of additional factors which are considered helpful to understanding the spatial and temporal patterns.

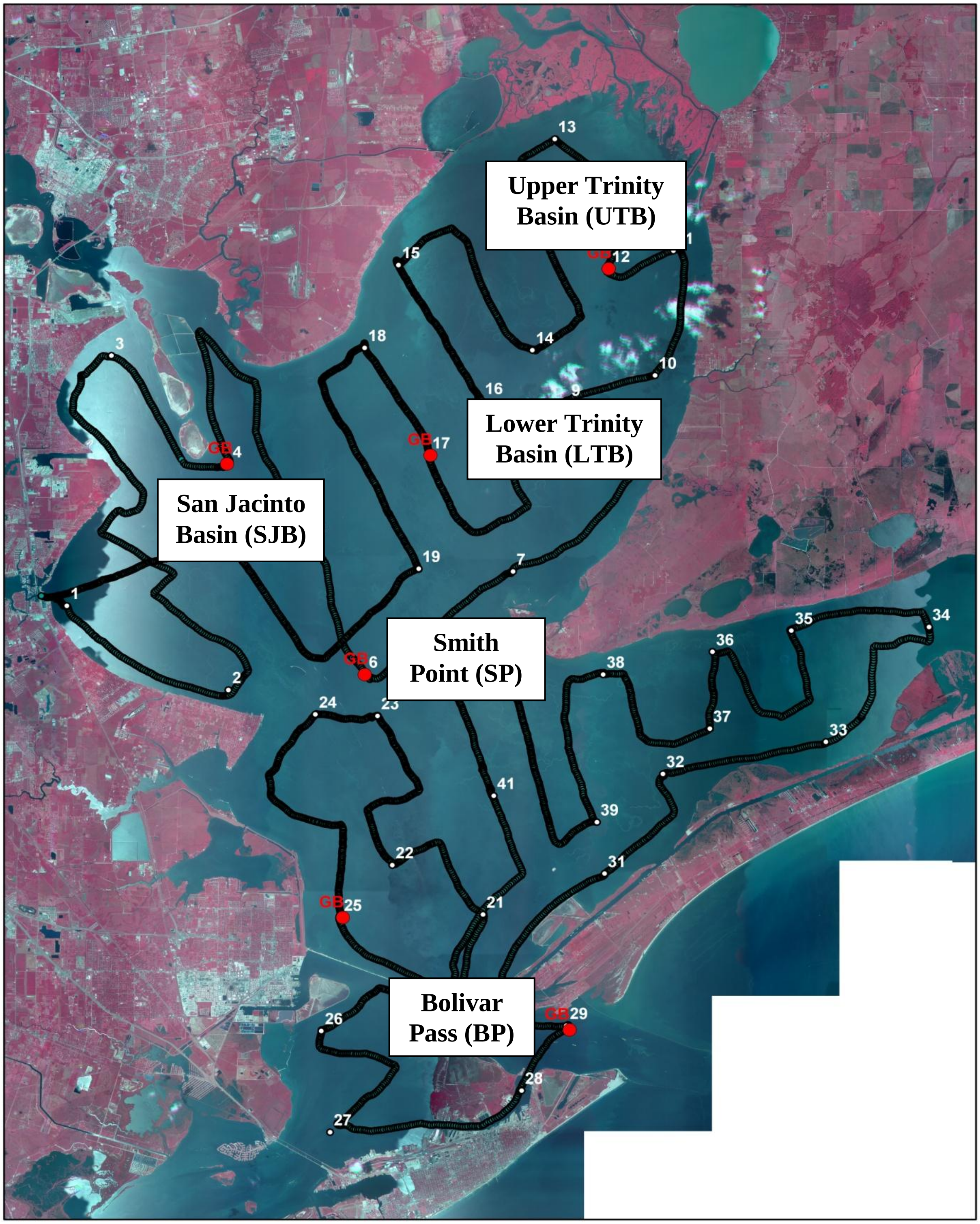


Fig. 1 Galveston Bay water quality parameters were examined along a tightly gridded transect shown by the black line. The northern part of the bay would typically take a day to complete, and the southern part a second day. Six fixed stations were sampled in order to check the calibration on the Dataflow. Ancillary measurements were also collected at stations in red as part of this project.

3.2 Resource Limitation Assays

Resource limitation assays (RLAs) were undertaken to identify which resource (nutrient(s) and/or light) limited phytoplankton growth at sampling sites in Galveston Bay during the study period. These bioassays were carried out essentially as described by Fisher et al. (1999) with modifications as described in Quigg et al. (2007, 2009b, 2010). Briefly, surface (0 - 0.5 m) water was collected in 20 L acid washed carboys (total thirty-two carboys) from two stations designated as North RLA and South RLA. Fig. 1 shows the location of RLA North (Station 17) and RLA South (Station 22) which are located at 29°37.01' N and 94°49.66' W and at 29°25.75' N and 94°50.68' W respectively. Water column temperature, pH, dissolved oxygen (DO), and salinity were measured with a calibrated Hydrolab sonde. An additional water sample (2 L) was taken from each site and returned to the laboratory – this water was used to measure the initial water quality (nutrients, TSS, etc...). Each bottle was triple rinsed with sample prior to filling. Triplicate carboys were then randomly selected for one of five treatments:

(i) a control (no addition),
(ii) + N (30 μmol L^{-1} NO_3^-),
(iii) + P (2 μmol L^{-1} PO_4^{3-}),
(iv) + NP (30 μmol L^{-1} NO_3^-, 2 μmol L^{-1} PO_4^{3-})
(v) “grazing” or GC.

in which nutrient concentrations are the final in each treatment. A “grazing control was prepared in which no nutrients were added (as done for the control) but for which water was pre-filtered with a 380 μm filter before filling each carboy. Treatments were incubated outdoors at ambient water temperature and turbulence and under 50% ambient sunlight in an outdoor facility (for details, refer to Quigg et al. 2009b). Treatments were then left for a week before being subsampled. The following parameters were then measured:

(i) phytoplankton productivity and biomass with a PHYTO-PAM,
(ii) nutrient concentrations (nitrate, nitrite, ammonia, phosphate) and,
(iii) total suspended sediments (TSS) and water column turbidity (Secchi depth),
(iv) dissolved organic matter (DOM) and total organic matter (TOC).

The response potential of phytoplankton in each treatment was quantified according to the phytoplankton response index (PRI) of (Fisher *et al.* 1999). The PRI was calculated by determining that the phytoplankton growth response is the ratio of the maximum biomass relative to the initial biomass. The response classification to accommodate for errors and temperature differences between assays was set to 140 fold > than the control.

In the original proposal, we planned to also examine the effect of a decrease of light availability: control (no addition), 10%, 25%, 50%, 100% shade cloth. Subsequently, we found that phytoplankton populations were generally not light limited in Galveston Bay (see Quigg et al. 2009b) hence these experiments were not performed at Stations RLA North (Station 17) and RLA South (Station 22). These experiments, may however, be performed in the future but at stations closer to the mouths of the Trinity and San Jacinto Rivers where turbidity may be sufficiently high as to lead to light-limitation of phytoplankton communities.

3.3 Phytoplankton Pulse - Amplitude Modulated Fluorometer (PHYTO-PAM)

The pulse-amplitude-modulation (PAM) measuring principle is based on selective amplification of a fluorescence signal which is measured in the presence of intense, but very short (µsec) pulses of actinic light. In the PHYTO-PAM, light pulses are generated by an array of light-emitting diodes featuring 4 different wavelengths: blue (470 nm), green (520 nm), light red (645 nm) and dark red (665 nm). This feature is very useful for distinguishing algae with different types of photosynthetic accessory pigments (Jakob et al. 2005). Green algae (Chlorophytes and Prasinophytes) can be distinguished from Diatoms plus Dinoflagellates and Cyanophyta.

Further, valuable information on the photosynthetic performance and light saturation characteristics of a phytoplankton community can be obtained by measuring the relative electron transport rate (*rel*ETR). Light response curves were generated by measuring the change in quantum yield with increasing light intensities. These resemble the photosynthesis-irradiance curves known from gas exchange and C14-fixation measurements (see details in Quigg et al. 2009b). The advantage of the PHYTO-PAM technique was that it can be done in minutes, it is non-invasive and requires no isotopes. Gas-exchange techniques and C14-fixation require hours to a day, isotopes for the latter technique and so restrict the total number of samples which can be examined. The PHYTO-PAM approach promises to be particularly suited to monitoring programs designed to assess inter-annual variability in phytoplankton community composition, productivity and biomass. It is sensitive to 0.1 µg chlorophyll L^{-1} (Nicklisch and Köhler 2001) and allows for statistically robust experimental design given many samples can be examined within a short period of time. A calibration curve was prepared which allowed the fluorescence signal (volts) to be converted to chlorophyll concentration (µg L^{-1}); in this way the output was used to determine phytoplankton biomass.

3.4 Nutrients

For nutrient (dissolved and total) analysis, water samples from each station were filtered (GF/F; Whatman) onto a filter under low vacuum (< 130 kPa) pressure. The filtrate was stored in an acid cleaned HDPE rectangular bottle (125 mL; Nalgene) which was triple rinsed with extra filtrate before keeping the final sample for analysis. Samples for nutrient analysis were frozen immediately until analysis was performed using analytical auto-analyzer according to Hansen and Koroleff (1999).

3.5 Total Suspended Solids

For measurement of total suspended solids (TSS), filters were pre-combusted (500ºC for 5 hrs) and pre-weighed. After filtration of a known volume of water, filters were dried in an oven at 60 ºC for no less than 48 hrs and then reweighed.

3.6 Total and Dissolved organic matter

Organic carbon analyses was performed in the Wetland Ecology Lab at Texas A&M University (College Station) using a Shimadzu 5000 TOC analyzer. Acceptable standard procedures were utilized in the analysis of each sample (APHA, 1998). Additionally, all analyses were done in accordance with standard QA/QC protocols for sample receiving, storage, and calibration/standardization.

4. Results

4.1 Freshwater Inflow into Galveston Bay during 2009

Real-time freshwater inflow measured as daily discharge to Galveston Bay from January 01 to December 31, 2009 was downloaded from the USGS monitoring station located on the Trinity River at Romayor (08066500). Monthly sampling campaigns (total of 10) are shown (red spots) on Figure 2. Almost 3 million cubic feet per sec (cfs) of water were discharged in 2009 (Fig. 2), most of which (about 1.67 million cfs) in the fall from early October to late December. As can be seen in Fig. 2, three additional significant freshwater inflow events (>10,000 cubic feet per sec) or freshets also occurred in 2009 during the spring: first during a four day period in March (total of 51,300 cfs), a second during a seven day period in April (total of 142,900 cfs) and the third, lasting almost two weeks early in May (total of 265,700 cfs). In 2009, there were significantly freshwater inflow events during the spring and fall months. Relative to the previous year, FWI in 2009 involved more discharge events across the year, and events of greater magnitude (Quigg et al. 2009b).

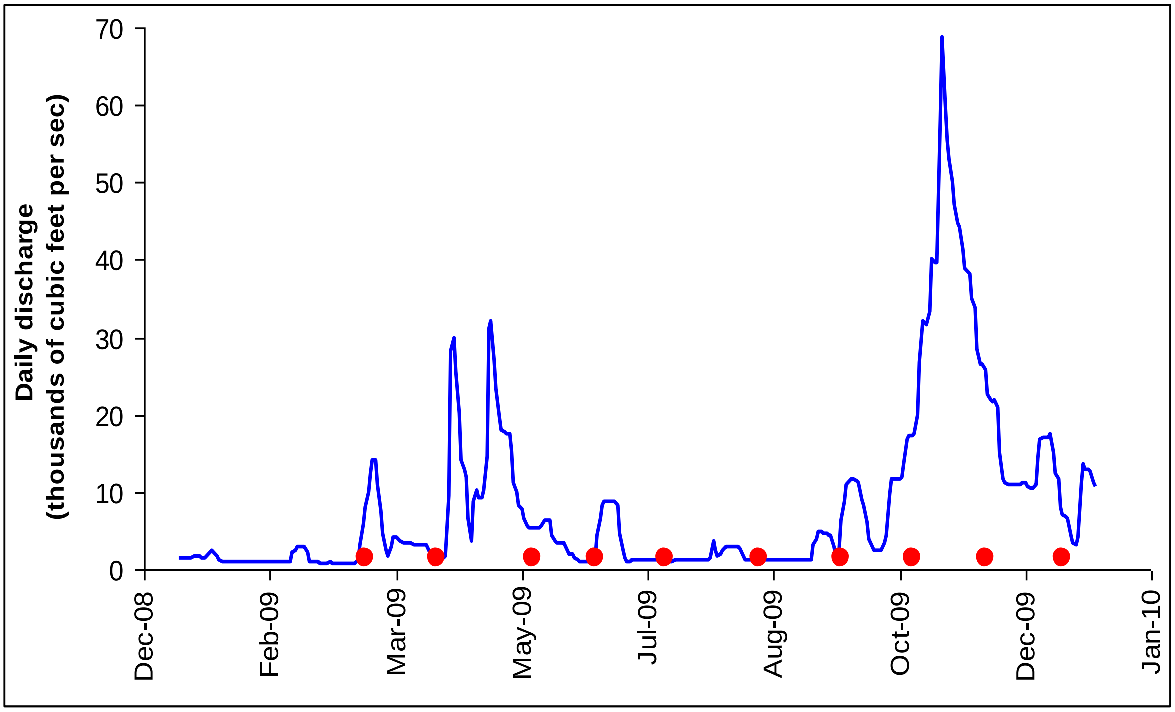


Fig. 2 Daily discharge of freshwater into Galveston Bay from January 01 to December 31 2009. Real-time flow data was downloaded from the USGS monitoring station located in the Trinity River at Romayor (08066500) located near the river's mouth. Red spots indicate timing of monthly field trips.

4.2 Temporal and spatial distributions of water quality parameters in Galveston Bay

The physio-chemical parameters mapped in Trinity-San Jacinto Estuary include water temperature, conductivity, salinity, water clarity, chl *a*, and dissolved organic matter. After sensor calibration and blank correction, data was imported into Surfer, a 3D contouring and surface plotting program. All Dataflow maps are included in Appendix A except for January and February in 2009. There is no data for these months due to boat repairs and poor weather (high winds) respectively preventing sampling.

Spatial characteristics of temperature, salinity, chl *a* and DOM for April and August 2009 are shown in Fig. 3 below. These months were chosen as they represent “wet” and “dry” periods respectively. Additional data is also shown for November which is a “very wet” period (Fig. 4). During April, water temperatures averaged 19.8°C ±1°C (Fig. 3A). By August 2009, temperatures had risen significantly to 31°C ±2°C. These temperature ranges are typical for this ecosystem (Davis et al. 2007; Quigg et al. 2007; 2009b, c). While salinities were significantly higher across Trinity-San Jacinto Estuary in August relative to April 2009 (Fig. 3B), they were also typical for these times of year. Average salinities of 19 (±4) reflected freshwater inflows in the Northern section of Galveston Bay in April. Corresponding salinities were 22 ±5 (Fig. 3B) with higher salinities in the Southern section of the Bay (31.5 ±5) in August. It can be seen that the large influx of freshwater inflows from the Trinity River (Fig. 2) had pushed the higher salinity waters out of the estuary towards the Gulf of Mexico (Fig. 3). This impact is most clearly seen in the November salinity maps (Fig. 4A). A gradient of salinities can be seen: 0 to 1 (0 – 1.7 mS cm^{-1}) in the Trinity River basin, to salinities of 5 -7 (7.5 to 10.1 mS cm^{-1}) in the middle of the estuary, and then salinities of 23 – 27 (29.4 to 33.9 mS cm^{-1}) near the mouth estuary – Bolivar Pass (Fig. 4). Salinities were generally higher on the west side of the Bay than on the east side reflecting the circulation patterns of the Bay. The magnitude of freshwater entering Trinity-San Jacinto Estuary early in the year had a long and significant influence of the system’s salinity gradient (refer to Appendix A). Highest salinities were recorded near the Bolivar and West Bay reflecting the interactions with the Gulf of Mexico and reduced circulation in this area due to the Texas City Dike respectively (Fig. 3).

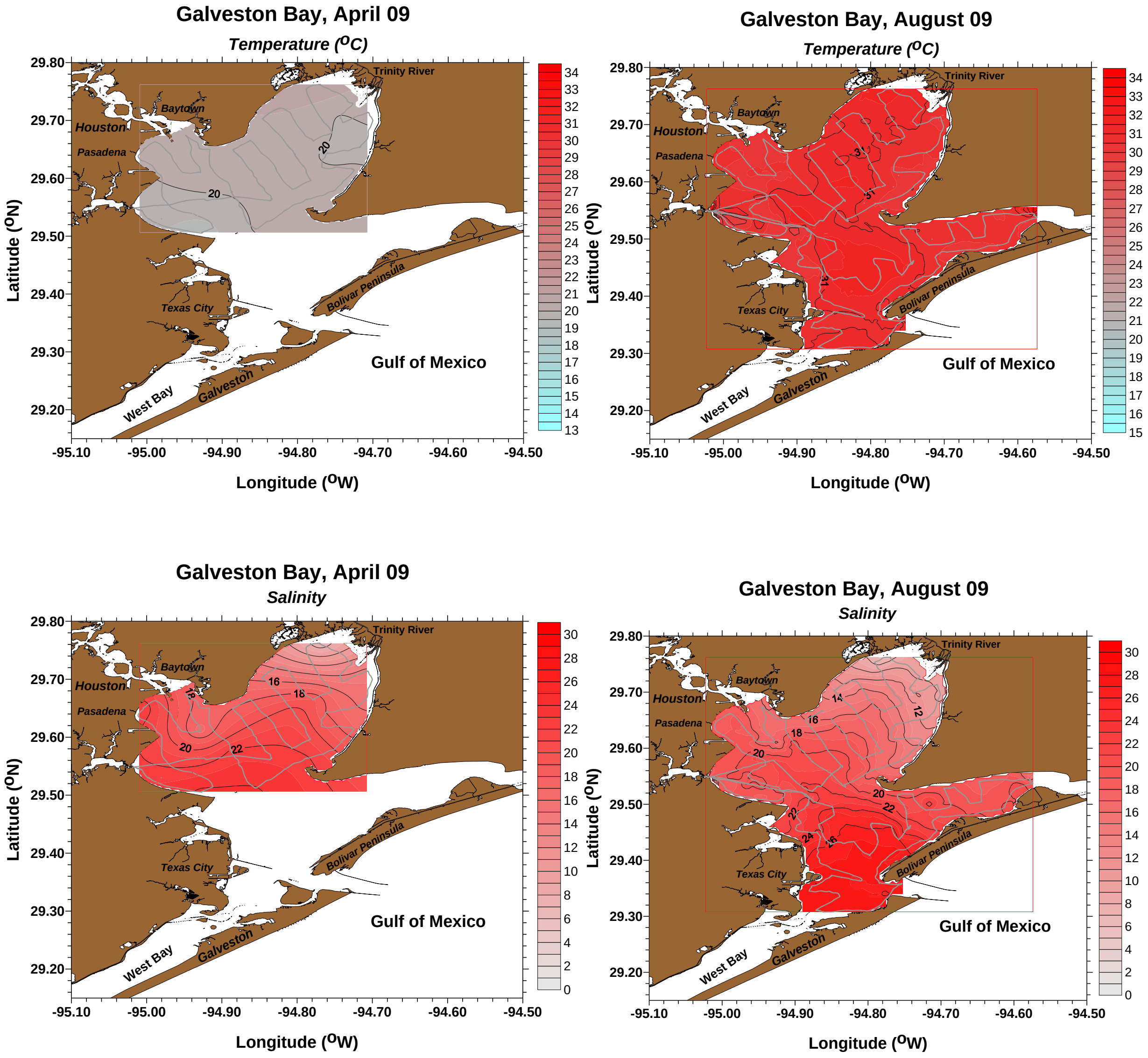


Fig. 3 Temporal (April and August 2009) and spatial patterns of (A) temperature (°C) and (B) salinity as measured with the Dataflow in Galveston Bay.

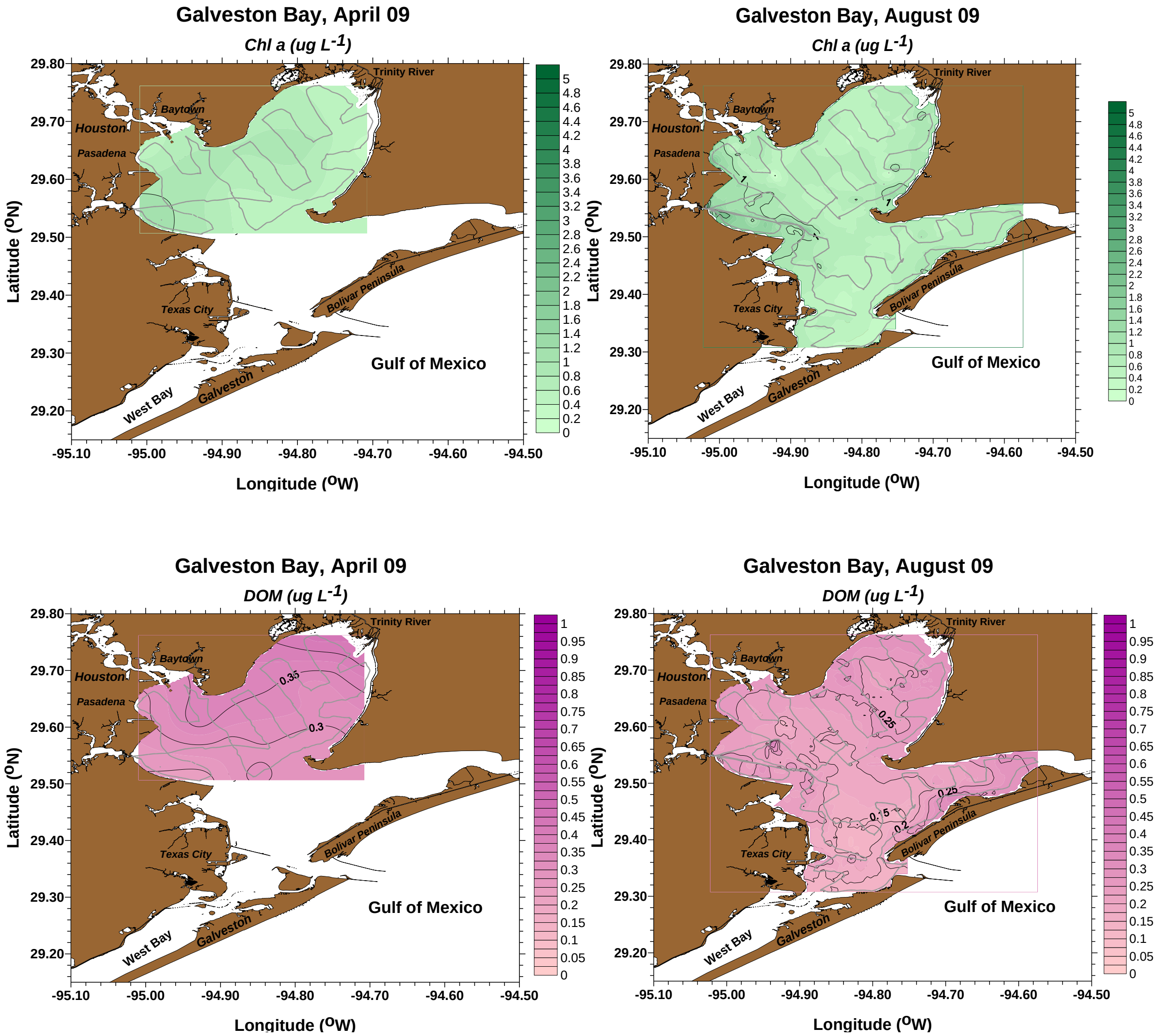


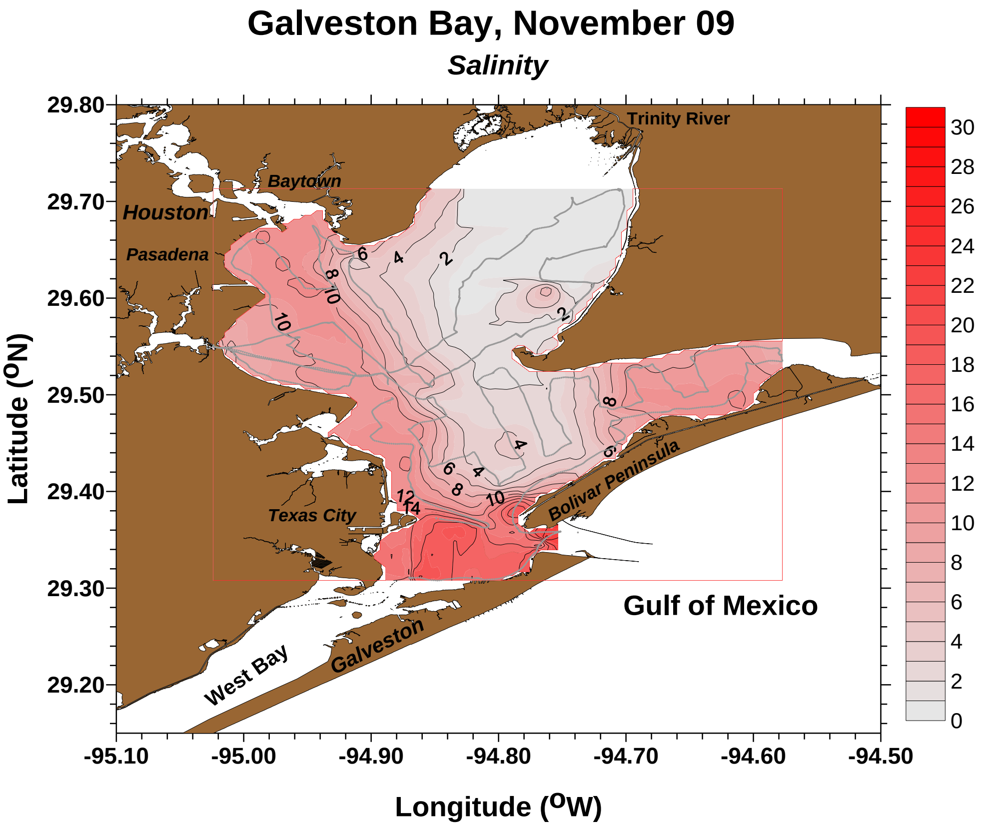
Fig. 3 Continued.

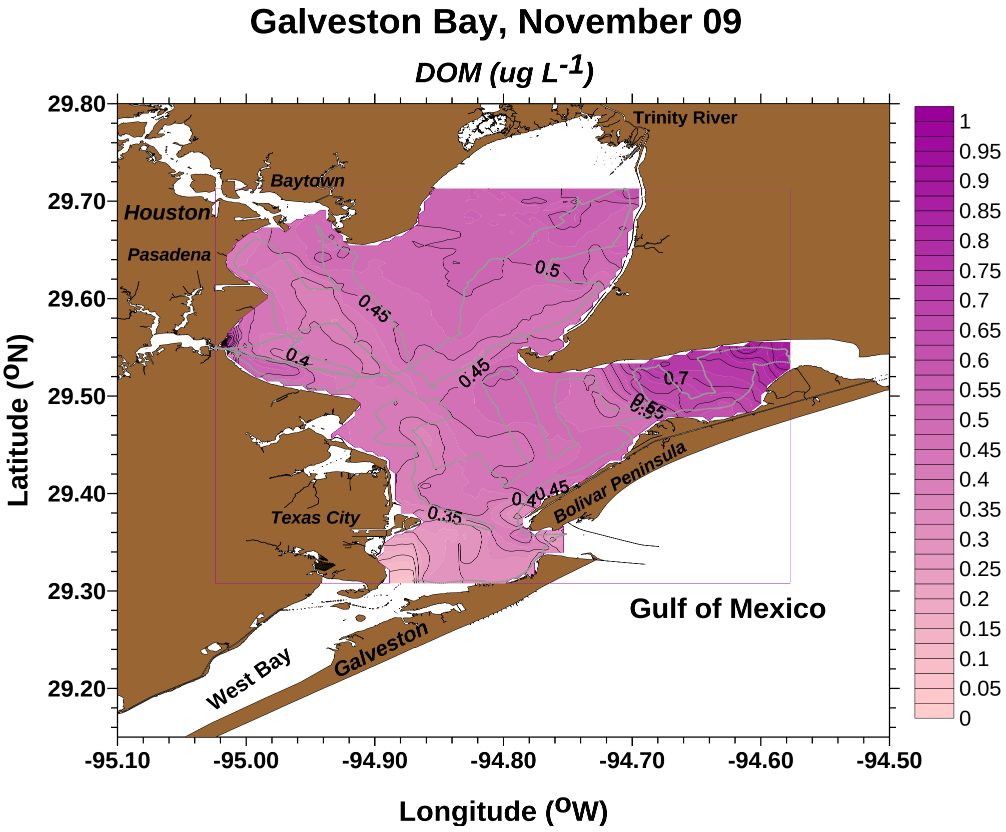
Temporal (April and August 2009) and spatial patterns of (C) in vivo chlorophyll a (ug L^{-1}) and (D) dissolved organic matter (ug L^{-1}) and as measured with the Dataflow in Galveston Bay.

Chl *a* concentration was measured as a proxy for the biomass of phytoplankton. In April (spring) and August (summer), chlorophyll concentrations were variable across the Trinity-San Jacinto Estuary (Fig. 3C). Chlorophyll concentrations were not significantly different between these two months – reflecting differential responses of phytoplankton to light availability (both in and out of the water column) and nutrients (dissolved and total particulate).

Aquatic ecosystems vary in the relative contribution of DOM from the catchment (allochthonous) and DOM produced within the system (autochthonous). The distribution of DOM in a water body provides details on the efficiency of carbon cycling in that system, by both the phototrophic community (that produce it) and the heterotrophic community (that consume it). As with the chlorophyll, spatial patterns differed but there was no significant difference in the amount of DOM in April and August in Galveston Bay (Fig. 3D). In both cases, there was less than 0.33 $\mu g\ l^{-1}$ on average across the bay. On the other hand, there was significantly more DOM in Galveston Bay in November 2009 (0.35 to 0.7 $\mu g\ l^{-1}$) (Fig. 4B). This latter finding suggests that allochthonous sources of DOM were the primary source after large freshwater inflow, while autochthonous maybe more important during low freshwater inflows. This finding is consistent with results from 2008 (Quigg, 2009). Further in November, and during other periods of high flows (see Appendix B), highest DOM concentrations are typically measured in East Bay.

Fig. 4 (Right) Spatial patterns of (A) salinity and (B) dissolved organic matter (ug L^{-1}) as measured with the Dataflow in Galveston Bay in November 2009, after a period of significant freshwater inflows. The significance is in relation to both the magnitude and duration as seen in Fig. 3 above.


Galveston Bay, November 09
Salinity
Latitude (°N)
Longitude (°W)
29.80
29.70
29.60
29.50
29.40
29.30
29.20
-95.10
-95.00
-94.90
-94.80
-94.70
-94.60
-94.50
Trinity River
Baytown
Houston
Pasadena
Texas City
Bolivar Peninsula
Gulf of Mexico
West Bay
Galveston
2
4
6
8
10
12
14
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0


Galveston Bay, November 09
DOM (ug L-1)
Latitude (°N)
Longitude (°W)
29.80
29.70
29.60
29.50
29.40
29.30
29.20
-95.10
-95.00
-94.90
-94.80
-94.70
-94.60
-94.50
Trinity River
Baytown
Houston
Pasadena
Texas City
Bolivar Peninsula
Gulf of Mexico
West Bay
Galveston
0.5
0.45
0.4
0.45
0.7
0.55
0.35
0.4
0.45
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0

4.3 Temporal patterns in water quality parameters in the northern and southern sections of Galveston Bay

Based on findings with the Dataflow and in previous studies (Quigg et al. 2007, 2009b), the Bay can qualitatively be divided into two sectors in terms of the influence of freshwater inflows on the phytoplankton community: North and South. Hence, resource limitations assays (RLAs) were undertaken to identify which resource (nutrient(s)) limited phytoplankton growth at two representative sites in Trinity-San Jacinto Estuary. RLAs were conducted in February, March, May, June, September, November and December 2009 in order to capture variations in freshwater inflow as well as seasonal changes in phytoplankton responses to nutrient and sediment loading. Unlike the Dataflow mapping (see section 4.2 above), we were able to conduct a RLA in February and so present these findings.

Before starting each RLA, water quality characteristics at RLA North and RLA South were defined. These are the characteristics of the "initial" conditions. Given the shallow nature (average depth of 2 m) of Galveston Bay, there were no gradients (e.g. temperature) observed when examining vertical profiles of the water quality at each station from surface to bottom at anytime during the year (Quigg et al. 2010). Hence, average water column values are presented. Natural oscillations followed annual cycles with summer highs of 30°C in June and winter lows of 12°C in December 2009 (Fig. 5A). pH also had summer highs, average of 8.87 ± 0.04 in June, and winter lows of 8.11 ± 0.02 in December, but even lower earlier in the year (5.32 ± 0.39 in February) as seen in Fig. 5B. Despite its well mixed nature, DO oscillations could be observed, driven largely by changes in water column temperatures (Fig. 5C). Hence, DO was typically 5.0 (± 0.33) mg L^{-1} in the summer but rose to 9.5 (± 0.13) mg L^{-1} in the winter.

Unlike the patterns observed for water column temperature, pH and DO, the following parameters were not always homogenous throughout the water column nor did they show seasonal oscillations. Rather, it can be argued that the following parameters were mostly influenced by freshwater inflows into Galveston Bay. This is further supported by differences seen between measurements at RLA North versus RLA South. Whilst this generalization holds in most cases, conflicts arise at RLA South because there is an additional influence of Gulf of Mexico waters which mix as they enter Galveston Bay at the inlet located at Bolivar Pass.

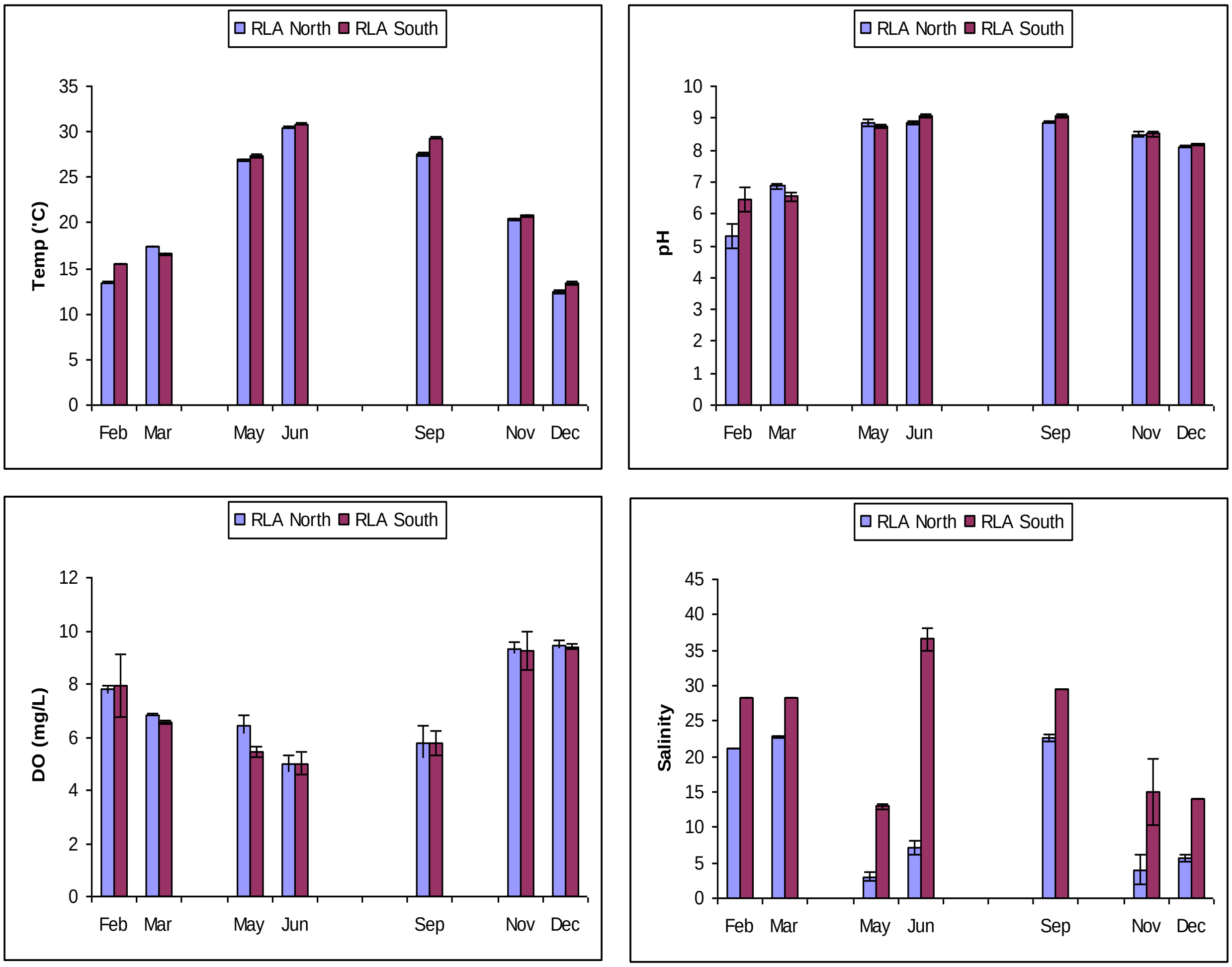


Fig. 5 Temporal patterns of (A) temperature (ºC),(B) pH,(C) DO (mg L^{-1}) and (D) salinity measured at RLA North (blue bars) and RLA south (purple bars)in Galveston Bay in 2009.

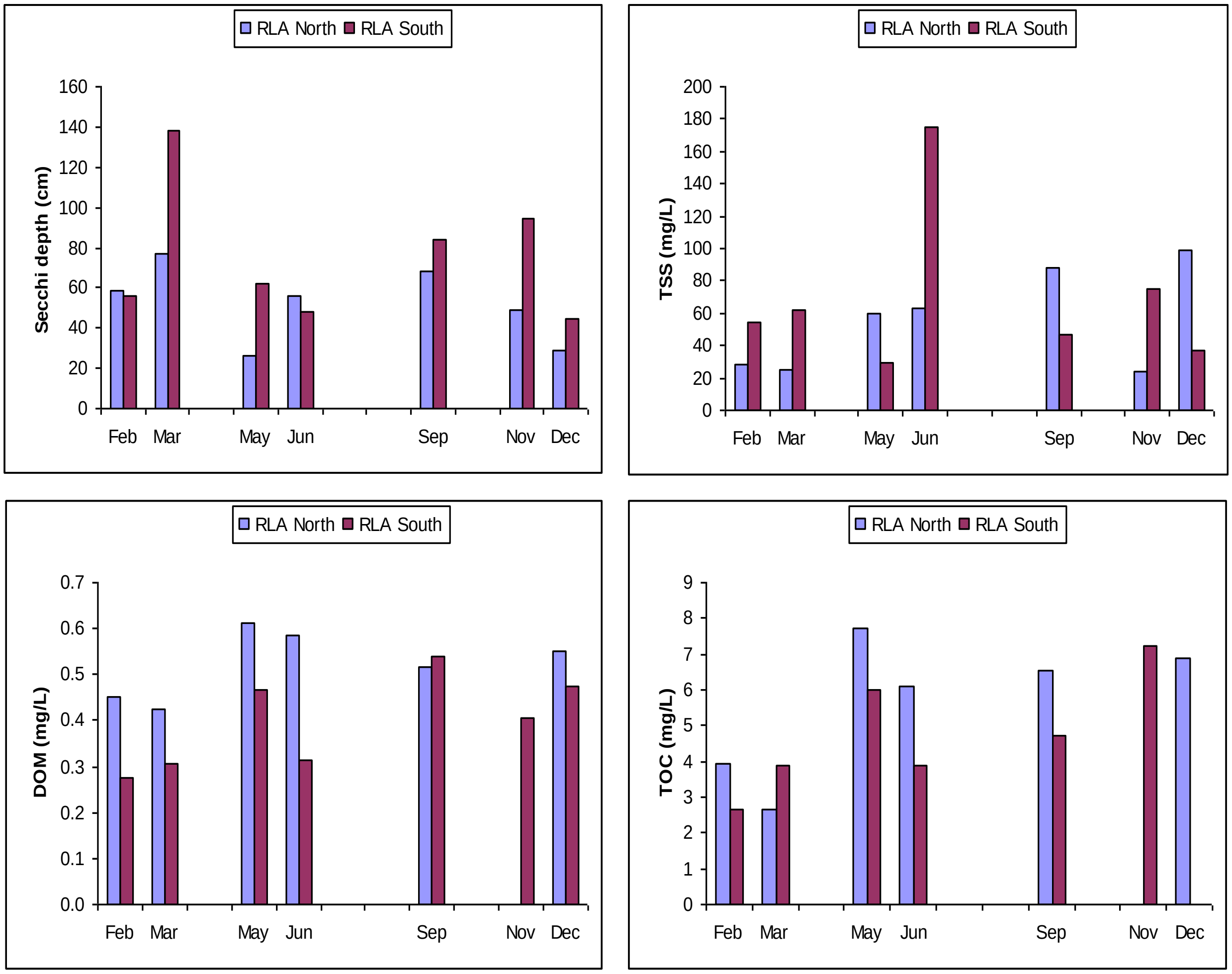


Fig. 5 Continued.
Temporal patterns of (E) Secchi depth (cm), (F) TSS (mg L^{-1}) ,(G) DOM (mg L^{-1}) and (H) TOC (mg L^{-1}) measured at RLA North (blue bars) and RLA south (purple bars)in Galveston Bay in 2009.

Patterns for salinity were far more complex (Fig. 5D). Again, the water column was found to be well mixed such that no halocline was observed at any station. Salinities were similar at each station in February and March: 21-22 at RLA North and 29-28 RLA South thus reflecting the estuarine gradient and a period of prolonged low flows (see Fig. 2). By May however, salinities were significantly lower at both RLA North (3.06 ±0.57) and RLA South (7.06 ± 0.99) as a result of a period of freshwater inflows in which three significant freshets (> 10,000 cfs) were recorded (Fig. 2). Salinities then slowly increased through the summer 22 (± 0.1) at RLA North and 29.5 (± 0.5) at RLA South (Fig. 5D). The large freshwater inflow event late in the fall effectively lowered the salinities in Galveston Bay starting in the northern section and moving slowly south as can be seen in Fig. 4 and in greater detail in the salinity maps presented in Appendix A.

Responding to these perturbations, water clarity (measured as Secchi depth) also responded to changes in salinity throughout Galveston Bay (Fig. 5E). In general, as salinities increased, so did Secchi depth (linear regression, r2 = 0.246, not shown). This general pattern was not station dependent as different factors clearly played a role at each station. For example, wind driven mixing events were more important at RLA South, perhaps because of its proximity to the Houston Ship Channel and mixing with Gulf of Mexico waters. At RLA North, greatest Secchi depths were recorded during periods of low flows, reflecting the decreased influence of particulates, silts and sediments which enter the Bay as part of flows, and lower the water clarity.

Total sediment loading in Galveston Bay was estimated from measurements of total suspended sediment (TSS) concentrations (Fig. 5F). There was generally less TSS in the water column at RLA North (< 100 mg L^{-1}) compared with RLA South (> 100 and < 200 mg L^{-1}). Again, this reflects perturbations at these different stations. In an ancillary study (Quigg 2010), it was found that TSS was higher in the entire Bay during the spring (46% of all TSS in 2009) and lowest in the summer (6% of all TSS in 2009). The winter data however was biased by the lack of available data in January and February (see Quigg 2010).

As part of this study, we also measured DOM concentrations in Galveston Bay at RLA North and RLA South (Fig. 5G). As with the findings from the Dataflow mapping (see Appendix A), there was no significant change in the amount of DOM throughout the year in Galveston Bay with only one exception. There was significantly more DOM (doubling) in Galveston Bay in November 2009 (see maps in Appendix A). This large increase in DOM may be the result of the large (in magnitude and duration) freshwater inflow event prior to the November RLA (Fig. 2) which may have increased the DOM pool. If the case, this finding implicates allochthonous sources of DOM as the primary sources in Galveston Bay after large freshwater inflow events, while autochthonous sources maybe more important during low freshwater inflows. Unfortunately there is no DOM value for November at RLA North. However, previous studies have made similar conclusions (e.g., Davis et al. 2007; Quigg et al. 2009; Quigg 2010).

Patterns for TOC in Galveston Bay were similar to those for DOM in that there were no temporal trends (Fig. 5H). Again, there was no TOC data available for November so the potential source of TOC cannot be clearly identified as part of this study. There was generally more TOC at RLA North than RLA South but this pattern was not consistent throughout the year. Findings for TOC and DOM mimicked those for chlorophyll (see Appendix A) which does suggest a link to phytoplankton.

4.4 Temporal patterns in nutrients in the northern and southern sections of Galveston Bay

Whilst temperature and light are important for phytoplankton growth, nutrients – and their different forms – ultimately determine the magnitude and duration of phytoplankton blooms, species dominance and other critical factors. Significant freshets (> 10,000 cfs) from the Trinity River were important in introducing dissolved nitrogen as nitrate+nitrite to the northern part of Galveston Bay in May and November but not ammonium (see RLA North, Table 1). Phosphate (dissolved) concentrations at RLA North and RLA South were independent of freshwater inflow events throughout 2009 (Table 1).

Station 17 RLA North	Month	[NO3+NO2]	[NH4]	[DIN]	[PO4]	[DIN:P]	[TN]	[TP]	[TN:TP]
	February	0.09	5.24	5.33	0.92	2.6	101.41	1.92	23.9
	March	4.48	3.70	8.18	1.39	2.7	123.21	3.14	17.7
	May	20.62	1.84	22.46	2.14	4.7	74.60	4.40	7.7
	June	0.65	4.65	5.30	2.54	0.9	49.79	4.91	4.6
	September	0.29	0.68	0.97	3.90	0.1	44.18	3.66	5.5
	November	13.87	1.17	15.04	0.49	13.9	65.87	3.97	7.5
	December	7.96	5.83	13.79	0.10	62.3	73.70	5.22	6.4

Station 22 RLA South	Month	[NO3+NO2]	[NH4]	[DIN]	[PO4]	[DIN:P]	[TN]	[TP]	[TN:TP]
	February	0.61	8.76	9.37	0.64	6.6	105.00	1.14	41.6
	March	0.55	0.90	1.45	0.68	1.0	98.28	1.67	26.6
	May	14.47	2.18	16.65	2.03	3.7	70.23	3.40	9.3
	June	1.73	3.35	5.08	1.02	2.2	61.11	2.50	11.0
	September	0.58	2.01	2.59	1.41	0.8	65.21	8.07	3.6
	November	11.93	1.25	13.18	0.37	16.1	69.86	4.18	7.5
	December	6.19	4.77	10.96	0.12	41.2	65.20	4.50	6.5

Table 1 Nutrient concentrations (total and dissolved; units are μM) measured at RLA North and RLA South prior to starting the RLAs at these locations. For ratios, nutrient concentrations were converted to molar ratio.

Given DIN:P ratio's greater than 12:1 suggest phosphorus will be limiting to phytoplankton growth, and DIN:P ratio's less than 7:1 suggest nitrogen will tend to be limiting for growth Wetzel (2001), these ratios were examined in samples collected across 2009. In all months RLAs (North and South) were conducted except for November and December, DIN:P ratios presented in Table 1 were less than 7.1, indicating a strong potential for N-limitation. On the other hand, measurements indicated a potential for phytoplankton P-limitation, particularly in December. This will be explored below.

While dissolved nutrient concentrations are those most bioavailable to phytoplankton, total particulate nutrient concentrations are nonetheless an important component of the water quality characteristics of any system and may be available to some fraction of the community. TN and TP concentrations measured at RLA North and South prior to starting assays. Consistent with our understanding that different processes regulate different nutrient fractions and patterns observed for total particulate nutrients were not identical to those observed for dissolved nutrients.

The total particulate nitrogen (TN) concentrations were generally higher (about double) earlier in the year (February and March) relative to those measured in the summer and fall (Table 1; Fig. 6). Total particulate phosphorus (TP) concentrations were variable during the year, but lowest concentrations were generally measured in the spring (about half of what was present the rest of the year. TN:TP ratios suggest a strong potential for P-limitation of phytoplankton predominantly in February and March (ratios > 35) whilst in the fall and early winter, TN:TP ratios (≤ 7.5) imply that there was the possibility for N-limitation (Table 5).

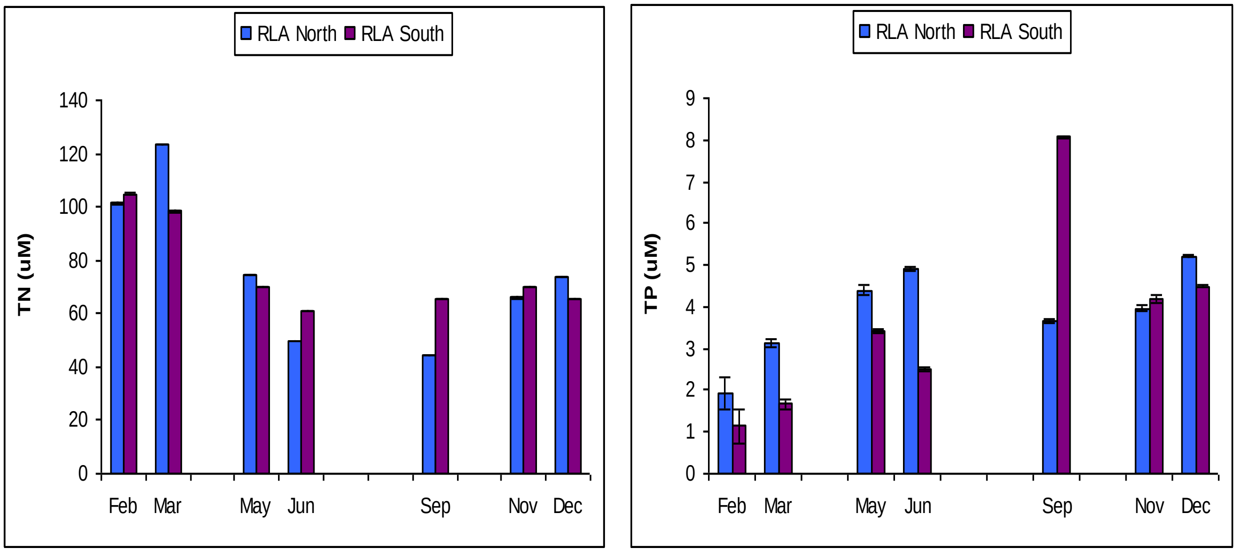


Fig. 6 Total particulate nitrogen (TN) and total particulate phosphorus (TP) measured at RLA North (blue bars) and RLA south (purple bars) in Galveston Bay in 2009.

4.5 Resource Limitation Assays

In Fig. 7, the average phytoplankton response index (PRI) was presented on a scale of 0 to 2700 for February and March and on a scale of 0 to 900 for the other months. RLA treatments in which nitrate was added (+N) and/or in treatments in which both nitrate and phosphate (+NP) were added together always yielded significant PRI measurements (Fig. 7). Hence, nitrogen as nitrate was primarily limiting phytoplankton growth at such stations. However, co-limitation of phytoplankton populations was important given the PRI’s in such treatments (+NP) were typically twice that measured in the +N treatments alone. For example, in February 2009, the PRI for the +N treatment was 640 and 1270 in RLA North (🟦) and RLA South (🟥) respectively while in the +NP treatments, the PRI was 1240 and 2570 in RLA North and RLA South respectively (Fig. 7). In March, the response in the +NP treatment for RLA South was actually four-fold greater than that in the +N alone treatment and 50-fold greater than in the control (Fig. 7). In several instances, phytoplankton responded more significantly in the +N and +NP treatments in RLA South than in RLA North – this occurred in February, May, June, September and December.

In RLA-North, conducted in May and June, there was no significant response to any treatment (Fig. 7). The addition of P as phosphate (+P) only elicited a significant response in RLA North in March and November and in RLA South in February (Fig. 7). In only one case - December - was a significant response observed in the control (Fig. 7); this occurred in both treatments. Given the only observed significant response of the phytoplankton in the grazing treatment also only occurred in both the December RLAs (Fig. 7); phytoplankton growth in this month was likely to be light limited, that is, a significant response was measured in all treatments including the control.

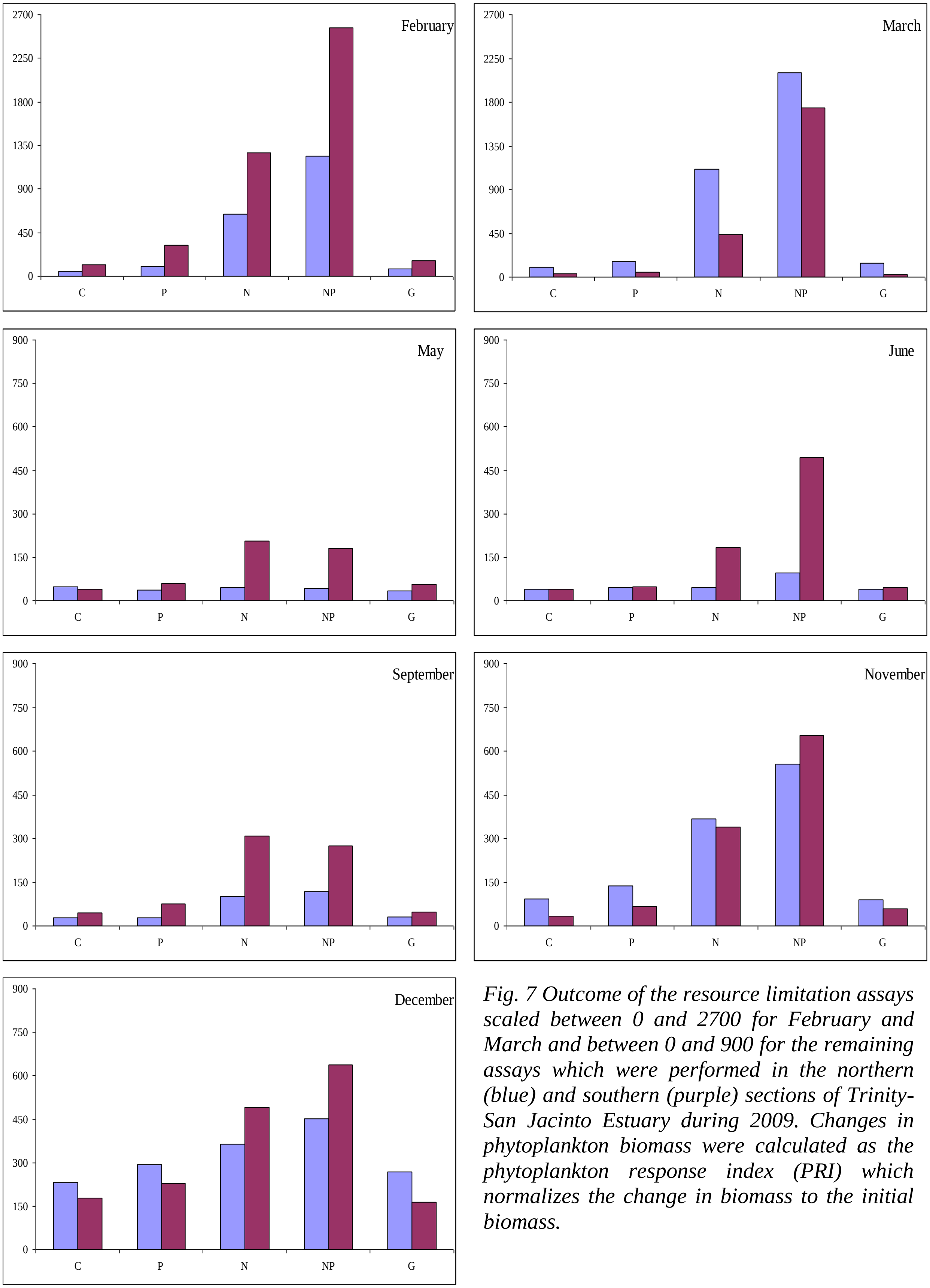


Fig. 7 Outcome of the resource limitation assays scaled between 0 and 2700 for February and March and between 0 and 900 for the remaining assays which were performed in the northern (blue) and southern (purple) sections of Trinity-San Jacinto Estuary during 2009. Changes in phytoplankton biomass were calculated as the phytoplankton response index (PRI) which normalizes the change in biomass to the initial biomass.

4.6 Phytoplankton community response to nutrient additions

The PHYTO-PAM uses different fluorescence wavelengths to distinguish between Cyanophyta (blue; 470 nm), green algae which includes both Chlorophytes and Prasinophytes (green; 520 nm) and Dinoflagellates plus Diatoms (light red; 645 nm) on the basis of their photosynthetic accessory pigments. As with findings from previous studies (Quigg et al. 2007, 2009b; Quigg 2009), the PHYTO-PAM did not detect Chlorophytes and Prasinophytes (green algae) during 2009 in Trinity-San Jacinto Estuary. This is now understood to reflect that concentrations of these groups are below the detection limits of this instrument rather than due to the absence of green algae from this ecosystem (Quigg 2009). Hence, changes in community composition will be limited to the activities of the major players in Galveston Bay, that is, the diatoms, dinoflagellates and cyanobacteria (see Örnólfsdóttir et al. 2004; Pinckney 2006; Quigg, et al. 2007; 2009b).

The PHYTO-PAM generated an enormous amount of data describing the interplay between the major phytoplankton groups in the RLAs. Upon closer examination, the highlights only have been presented below in Fig. 8. Based on results of the biomass changes (shown in Fig. 7), the most significant response observed was that to the addition of both N and P, that is the, +NP treatments. Hence, a comparison between the control (no addition) and +NP treatments from each of the RLAs is given. In all cases, diatoms and dinoflagellates (orange bars; 🟧) were dominant in terms of biomass over the cyanobacteria (blue bars; 🟦) (Fig. 8). Typically diatoms and dinoflagellates are more dominant in the cooler months while cyanobacteria are more dominant in the warmer months (e.g., Örnólfsdóttir et al. 2004; Quigg, et al. 2007; 2009). While this is apparent for the cyanobacteria in the controls, it is not clear for the diatoms and dinoflagellates (Fig. 8 – top two panels). Interestingly, in the +NP treatments (Fig. 8 – bottom two panels), this pattern is much more evident. Hence, while seasonal oscillations were the primary factor regulating these populations, secondary, was the addition of nutrients. Spatially significant responses were also observed. In the RLAs conducted at the northern station (RLA North; Fig. 8 – left two panels), cyanobacteria, when present, responded similarly in both the control and the +NP treatments. However, in the RLAs conducted in May and June at the southern station (RLA South; Fig. 8 – right two panels), cyanobacteria showed a greater response (2- to 4-fold) in the +NP treatments compared to the controls. In November, the opposite was true (this is also the month of the highest flow for 2009 – see Fig. 2). When examining the response of the diatoms and dinoflagellates, there were significantly less present in the southern station relative to the northern station in both the control and the +NP treatments (Fig. 8) with a few exceptions (e.g., March -- RLA South > RLA North).

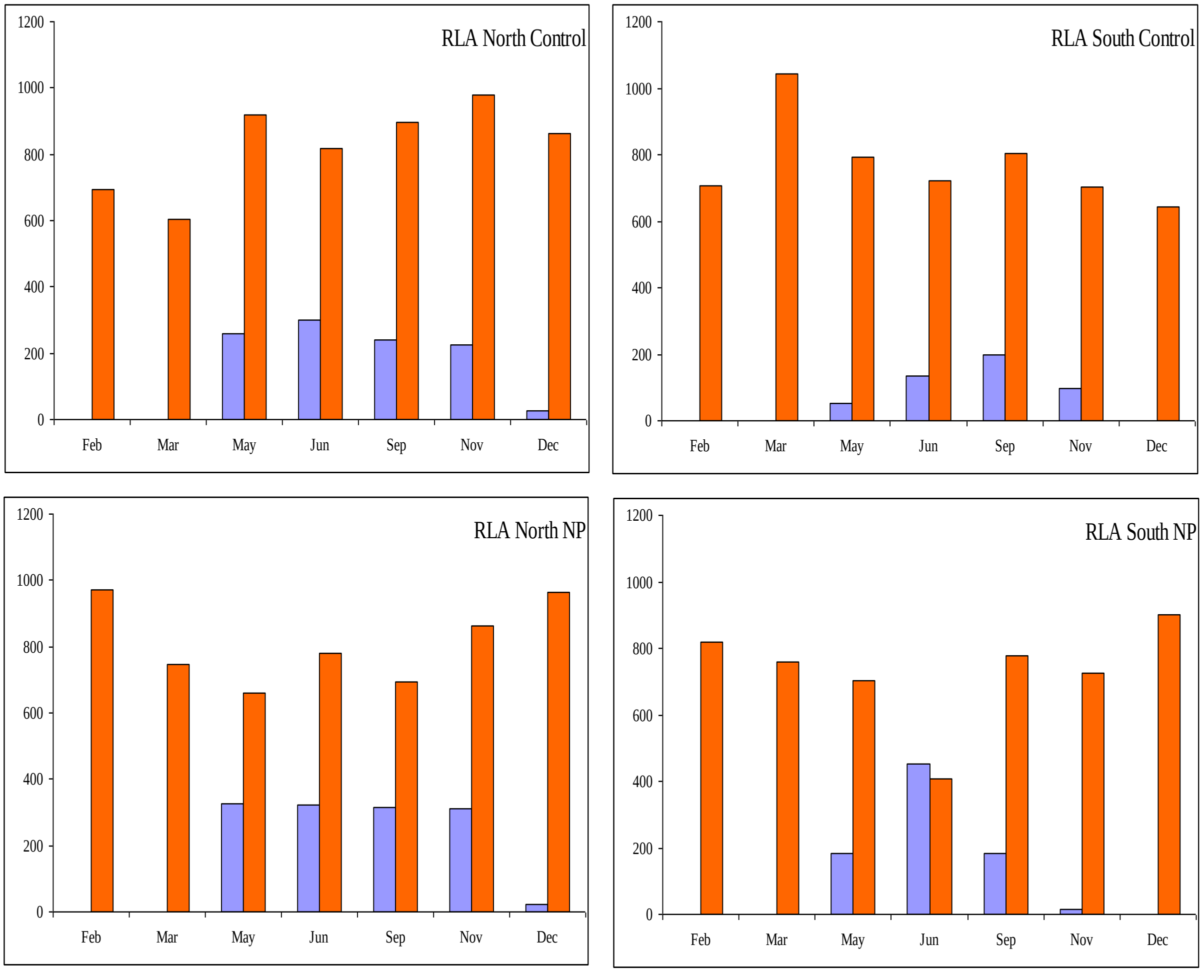


Fig. 8 Response of diatoms and dinoflagellates (orange bars) and cyanobacteria (blue bars) in the RLAs conducted across 2009; top panels – controls (no addition), bottom panels - +NP treatment. The y-axis is the relative biomass (F) of each group measured with the PHYTO-PAM.

Given the findings already presented, and in order to further simplify so as to present only the major outcomes, the results for the measurement of relative electron transport chain (*rel*ETR) which will be used as a proxy for productivity are those for only the control (no addition) and NP treatments (Fig. 9). A comparison of the outcomes for the major players was performed: diatoms and dinoflagellates (orange bars; 🟧) and cyanobacteria (blue bars; 🟦) (Fig. 9). If you consider that the diatoms and dinoflagellates dominate the water column in the cooler months, the three-fold greater phytoplankton biomass measured in the RLAs in February and March (Fig. 8) was supported by greater *rel*ETRs at the northern (Fig. 9 – top, left) and southern stations (Fig. 9 – top, right) when examining the control treatments. However, this finding was not obvious in the +NP treatments (Fig. 9 lower panels). *rel*ETRs of 140-150 µmol electrons m^{-2} s^{-1} where measured for the diatoms and dinoflagellates (🟧) in RLA North in February and March while in September and November, *rel*ETRs of 45-70 µmol electrons m^{-2} s^{-1} were measured, which are significantly lower (Fig. 9, top, left). A similar scenario was found at RLA South, with *rel*ETRs of 60-90 µmol electrons m^{-2} s^{-1} measured for the diatoms and dinoflagellates in February and March (Fig. 9, top, right). In September and November, *rel*ETRs of 30-50 µmol electrons m^{-2} s^{-1} were observed, almost half of the values measured in February and March (Fig. 9, top, right). Consistent with the findings presented in Fig. 8 above, cyanobacteria (🟦) were more important in the summer and fall. While at the northern station (Fig. 9, top, left), cyanobacterial *rel*ETRs ranged from 120-140 µmol electrons m^{-2} s^{-1}, those at the southern station were only significant in November (120 ± 15 µmol electrons m^{-2} s^{-1}) as seen in Fig. 9 (top, right).

In the NP treatments, *rel*ETRs were either lower (RLA North) or similar (RLA South) (Fig. 9, bottom, left and right, respectively) suggesting a complex interaction effect where phytoplankton responded to both the increase in nutrients but also to the decrease in space and light availability as populations increased in the NP treatments. Also apparent, is that the major players responded differently to the nutrient additions – on both the spatial and temporal scales. To really understand these findings, they will have to be considered in the context of the water quality and other parameters measured. That *rel*ETRs were either lower in the RLA North NP treatments relative to the control treatments may also support the contention that phytoplankton in the northern section of the Trinity-San Jacinto Estuary are accustomed to pulses of nutrients associated with freshwater inflows, and so respond less strongly. Phytoplankton populations in the southern section receive such nutrient pulses less frequently and so respond more strongly. Complicating this response is the competition between different phytoplankton present at different times. This finding is particularly interesting and will be the focus of future research efforts.

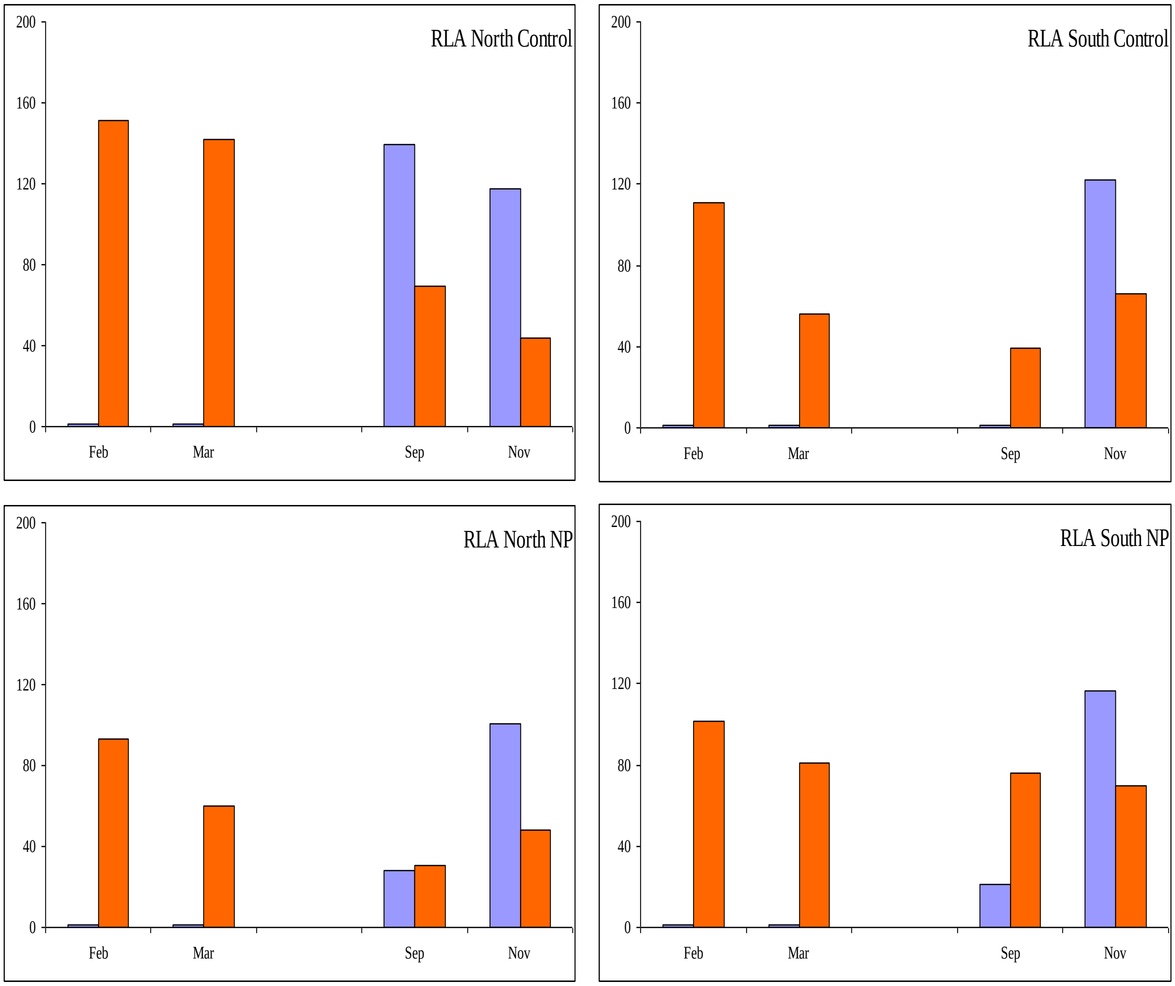


Fig. 9 Response of diatoms and Dinoflagellates (orange bars) and cyanobacteria (blue bars) in RLAs conducted across 2009. Top panels – controls (no addition), bottom panels - +NP treatment. The y-axis is the relative electron transport rate (relETR) of each group measured with the PHYTO-PAM.

5. Discussion

With a rapidly expanding urban population in Texas coastal municipalities (TWDB 2001, 2007), water regulators and managers are faced with the challenge of meeting rising human needs for water supply and water quality, while maintaining critical freshwater inflows to estuaries to preserve ecosystem health. The Galveston Bay Estuary Program identified an "*examination of the impacts of freshwater inflow and bay circulation*" as a priority area in its comprehensive conservation management action plan for 2001-2005 (GBEP, 2001; Longley 1994). Specifically to address Section 11.147 (a) of the Texas Water Code which defines "*beneficial inflows*" as those that provide a "*salinity, nutrient, and sediment loading regime adequate to maintain an ecologically sound environment in the receiving bay and estuary system that is necessary for the maintenance of productivity of economically important and ecologically characteristic sport or commercial fish and shellfish species and estuarine life upon which such fish and shellfish are dependent*".

Freshwater inflows and the degree of nutrient and sediment loading are important factors contributing to water quality and ecosystem health in estuaries (Longley, 1994; Nixon 1995; Howarth et al. 1988; Howarth and Marino 2006). Factors equally important, but not as often addressed, include the magnitude of flushing and nutrient loading, the mode of nutrient loading, and the ratios of potentially limiting nutrients within the load (Malone et al, 1988; Chan and Hamilton, 2001). Buyukates and Roelke (2005) found that plankton assemblages receiving nutrient loads in a pulsed mode had less accumulated phytoplankton biomass and supported greater secondary productivity, while assemblages receiving a continuous inflow resulted in a phytoplankton bloom and demise of the zooplankton community. Shifts in phytoplankton community composition and physiology are likely to change the nutritional value of phytoplankton to consumers, ranging from zooplankton to higher trophic levels. A clear understanding of the downstream ecological impacts of changes in freshwater inflows on estuaries remains a priority for resource managers and scientists alike.

Never has this been more apparent than in the last decade. The cumulation of efforts in Texas resulted in the creation of House Bill (HB) 3 and Senate Bill (SB) 3 during the 80th Texas Legislature in 2007 (see introduction for reference to details on SB3). Senate Bill 3 begins the implementation of the state's 50-year water plan. It recognizes the importance of the ecological soundness of our riverine, bay, and estuary systems and riparian lands has on the economy, health, and well-being of our state. Further, it requires the TCEQ adopt, by rule, appropriate environmental flow standards for each river basin and bay system in the state. Whilst this has not been done for all the bays and basins along the Texas coast, the final environmental flow recommendations report from the Sabine and Neches Rivers and Sabine Lake Bay Basin and Bay Expert Science Team and Stakeholder Committee (http://www.tceq.state.tx.us/permitting/water_supply/water_rights/eflows/) is available. This is also the case for Galveston Bay but the outcome is more complex. Two separate recommendations were submitted by the members of the Trinity-San Jacinto Basin and Bay Expert Science Team. They can be found below along with the transmittal letter to the Environmental Flows Advisory Group and a list of the members who endorsed each recommendation. These recommendations and much more information can be found here: http://www.tceq.state.tx.us/permitting/water_supply/water_rights/eflows/trinsanjacgalbaystake.html where the reader is referred to an excellent website. Nonetheless, a joint meeting of the Trinity and San Jacinto Rivers and Galveston Bay Stakeholder Committee and Expert Science Team will take place on Wednesday, October 6, 2010 and will initiate the development of the next phase, a work plan that satisfies Section 11.02362(p) of the Texas Water Code.

This study built on earlier findings of several CMP projects (see Quigg et al. 2007 and 2009b), as well as projects funded by the Texas Water Development Board (see Quigg 2009 and 2010), the Galveston Bay Estuary Program (Quigg 2009) and Texas Sea Grant (in preparation for February 2011). Collectively, we have fine spatial (approx. every 10m) scale maps of water quality parameters (e.g., salinity, temperature, chlorophyll) on monthly time scales from June 2005 to November 2006 (Davis et al. 2007) and from January 2008 to the present. We also have basic nutrient, primary productivity, and phytoplankton community analyses for fixed stations in Galveston Bay (Davis et al. 2007 Quigg et al., 2007; 2009b,c).

The current program focused specifically on the components of the nutrient and sediment load and how these impact primary production in Galveston Bay**.** There is little if no information on the composition of returned flows, specifically if there are elevated pollutants, nutrients or other elements we need to consider. Increased ammonia or urea from e.g., waste water treatment facilities would significantly alter phytoplankton community composition by favoring some groups over others. Initial data collected has revealed higher nutrient concentrations in the San Jacinto River basin than in the Trinity River basin (Quigg et al. 2009; Quigg 2010). Changes in the sediment distribution – i.e., a larger fraction of finer particles, or total suspended load fractions of organic versus mineral matter, could potentially reduce water clarity for longer periods of time and consequently, potentially reduce primary production. Whilst we have a good handle on the sediments coming down the Trinity River (Quigg 2010), less is known about those coming along the San Jacinto River.

5.1 Freshwater inflows

Natural freshwater inflows are known to vary in magnitude and duration, with most significant flow events in Texas occurring in Fall and Spring and little or no significant flow occurring in during the summer. This was certainly the case in 2009 with three major flow events, or freshets, (>10,000 cfs) in the spring and one in the fall. Compared to previous years this decade, 2009 could be considered a “wet” year (Table 2). Highest flows since 2000 occurred in 2001 and 2007 whilst lowest flows occurred in the corresponding proceeding years (2000 and 2006 respectively) (Table 2). Unlike 2008, there were no major hurricanes in the summer of 2009 influencing freshwater inflows (see Quigg et al. 2009b).

Period of record	**Average Discharge (cfs × 1000)**	**Wet or Dry**
2000	2,957	dry
2001	14,900	wet
2002	8,193	wet
2003	9,113	wet
2004	9,757	wet
2005	8,858	wet
2006	1,828	dry
2007	14,480	wet
2008	6,214	wet
2009	8,182	wet

Table 2 Annual discharge (cfs × 1000) measured at the USGS monitoring gage located on the Trinity River at Romayor (08066500) from 2000 to 2009.

A very large freshest was observed in the Fall of 2009 – large in both duration and magnitude. The influence of this inflow event was seen across the northern and the upper sections of the bay as well as some of the southern portions of Bay, pushing out previously higher salinity waters towards the Gulf of Mexico (Fig. 4A). At the same time, dissolved organic matter concentrations increased across the Bay in response to this influx of freshwater (Fig. 4B). Year round however, the response was clearly dependent on the magnitude of the freshwater inflow event and to a lesser extent, on the timing (see maps in Appendix A for further detail).

5.2 Interactions between phytoplankton and nutrients in Galveston Bay

The pulsed hydrology observed in Galveston Bay is common in many estuaries and can account for much of the annual loading of nutrients and sediment (Brock 2001; Paerl et al. 2001; Davis et al. 2007). Chl *a* concentrations, measured as a proxy for the biomass of phytoplankton, did not respond linearly to freshwater inflows – reflecting differential responses of phytoplankton to temperature, light availability (both in and out of the water column) and nutrients (dissolved and total particulate). Nitrogen concentrations during high flow periods such as the large freshets (> 10,000 cfs) from the Trinity River in May and November 2009 were important in introducing dissolved nitrogen as nitrate+nitrite to the northern part of Galveston Bay but not ammonium. During low flow periods, nitrogen concentrations are close to the baseline previously reported by others (Davis et al. 2007; Quigg et al. 2009b). Phosphate (dissolved) concentrations at RLA North and RLA South were independent of freshwater inflow events throughout 2009 (Table 1). On the other hand, the total particulate nitrogen (TN) concentrations were almost double in the winter and spring relative to summer and fall. This is similar to the previously reported patterns for this ecosystem (Quigg et al. 2007, 2009; Quigg 2009). It appears that dissolved nutrient loads are regulated by allochthonous processes (freshwater inflows) while particulate loads are regulated by autochthonous processes. For the latter, higher particulate loading appears to reflect nutrient loading associated with the Houston Ship Channel, urbanization and industrialization along the upper San Jacinto River complex and wind driven mixing towards the opening of Trinity-San Jacinto Estuary with the Gulf of Mexico at the southern most end of the Bay.

Despite these nutrient levels, DIN:P ratios and RLAs generally pointed to phytoplankton being N limited during most of the year but particularly in the warmer months, when there was very little freshwater inflows (Table 1; Fig. 7). Similar such results are consistent with earlier similar studies in Galveston Bay (Örnólfsdóttir et al. 2004; Pinckney 2006; Quigg et al. 2007, 2009; Quigg 2009). P limitation, when measured, occurred during periods when freshwater inflows were of greatest magnitude and duration. These findings are consistent with the observations of many studies that phosphorus is the proximal limiting nutrient element of concern in fresh waters, while nitrogen is the proximal nutrient limiting productivity in marine systems (Nixon, 1995; Howarth and Marino, 2006).

Further, according to the RLAs, phytoplankton were also frequently co-limited by both N- and P-sources during 2009. In the RLAs performed in the northern part of the Trinity-San Jacinto Estuary in February, March, November and December, the response to the addition of NP always elicited a stronger response than the addition of N alone (Fig. 7). On the other hand, there was no significant response in RLAs conducted from May to September. This typically only occurs when phytoplankton are neither light nor nutrient limited. Given that the nutrient ratios and RLAs in this part of the Bay do not provide entirely the same conclusions (not unexpected based on previous published studies), possible alternative explanations were examined. Diatoms and dinoflagellates dominate in the cooler months while cyanobacteria dominate in the warmer months. Hence, the findings in these RLAs may also reflect seasonal cycles associated with phytoplankton communities. This conclusion fell however, when examining the findings of the RLAs in the southern section of the Bay. In those, limitation by NP and N was observed year round. The additional explanation for this finding is that given that these waters are mostly dominated by inputs from the Gulf of Mexico, they have lower overall nutrient concentrations leaving phytoplankton nutrient-limited all year. Previous studies have also reported that different phytoplankton groups have different affinities for the major nutrients; thus, taxon specific trends have been observed. For example, Tilman et al. (1986) reported that diatoms dominate in ecosystems with high N:P or when phosphate concentrations are low while cyanobacteria outcompete other groups under low N:P ratios. Our findings are consistent with these generalities from earlier studies. In addition, the results suggest the nutrient concentrations did not provide balanced growth for phytoplankton communities in Galveston Bay.

While in 2008 there was also wide spread co-limitation of phytoplankton production by nitrogen and phosphorus (Quigg 2009); there was also the observation that the greatest phytoplankton response indices were always measured in RLA South. This clear pattern was not observed in 2009 – the simplest rationale perhaps is the difference in flow patterns between years and hence the distribution and magnitude of nutrient loading. However, a clearer understanding will required multivariate statistics, and more importantly, several more years of data to determine which responses are seasonal or annual versus those which can be truly related to freshwater inflow events.

6. Conclusions and future directions

This study contributes to the improved understanding of how the present Trinity-San Jacinto Estuary ecosystem complex responds to freshwater inflows – pulses, high flow and low flow periods – in order to develop a conceptual understanding of the downstream ecological impacts of future changes to freshwater inflows and modes of nutrient loading into this system. The Galveston Bay area is likely to see the largest population growth along the Texas coast in the next few decades (TPWD, 2001, 2007). We need to understand how the present Galveston Bay ecosystem responds to nutrient and sediment loading from freshwater inflows in order to develop a conceptual understanding of the downstream ecological impacts of future mitigation strategies for freshwater inflows. Future studies should consider the role of nutrients in sediments, and sediment-water interactions (see also Quigg 2010). Given the shallow nature of the Bay and the importance of wind mixing, an understanding of processes taking place at the sediment-water boundary will be needed to fully develop a nutrient budget. The transfer of carbon derived from phytoplankton can either mediate or amplify the effects of nutrient loading and eutrophication as the material is exported or remineralized, respectively (Pinckney, 2006; Howarth and Marino, 2006). Hence, we need to gain an understanding of all the steps in the loop before a nutrient budget can truly be developed. This program endeavored to address goals stated in the TGLO-CMP documents, specifically those associated with water supply and quality. The information collected will be made publicly available on the PI's websites on the TAMU server with links to the appropriate agencies. This project will contribute to the state's efforts to improve resource management by providing basic information necessary for sound implementation of CMP goals and policies.

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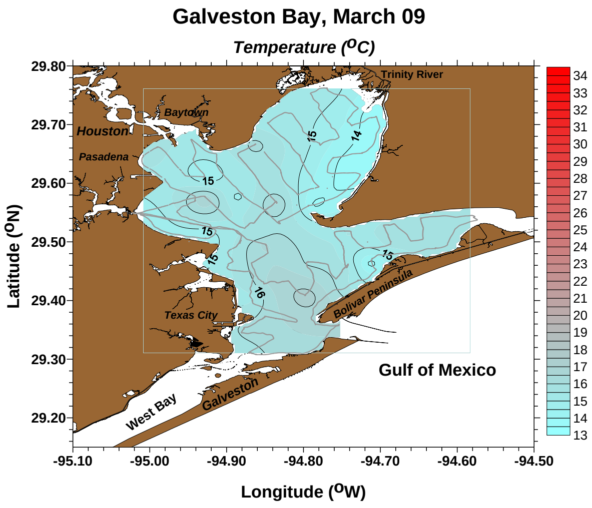
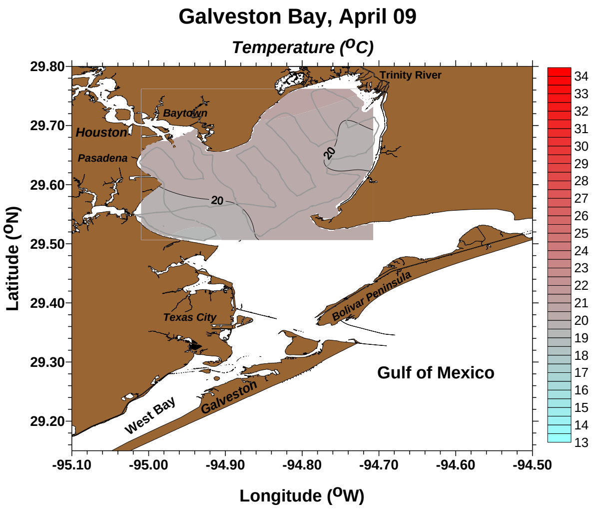
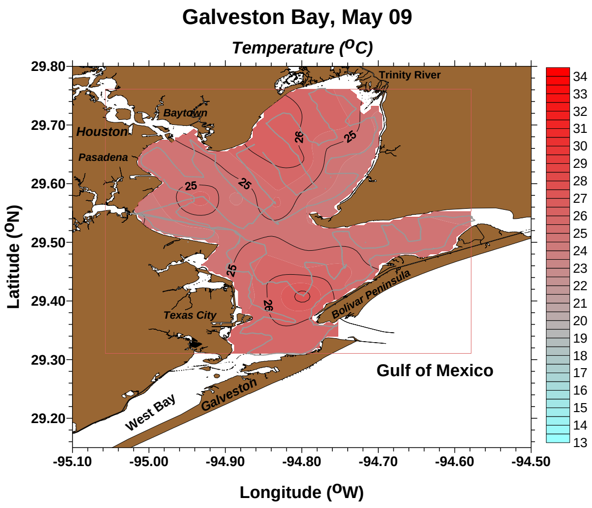
Appendix A

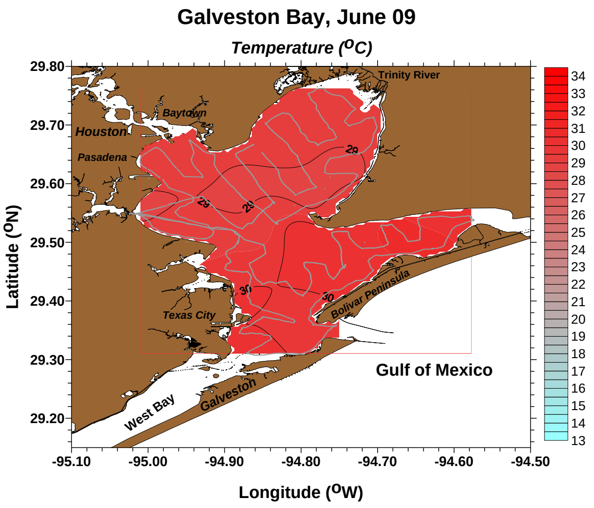
Monthly spatial maps with water quality parameters measured using the Dataflow.

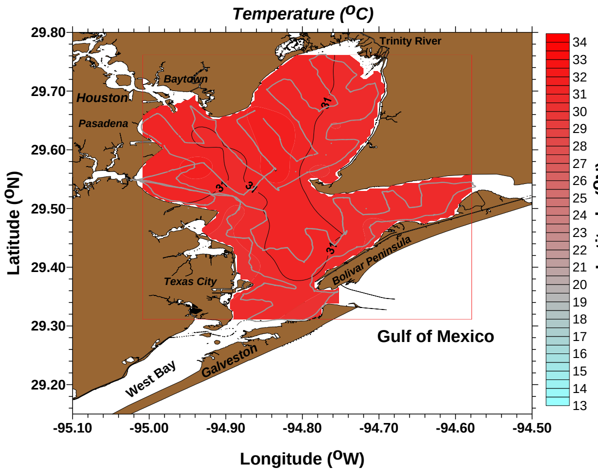
Temperature (°C)











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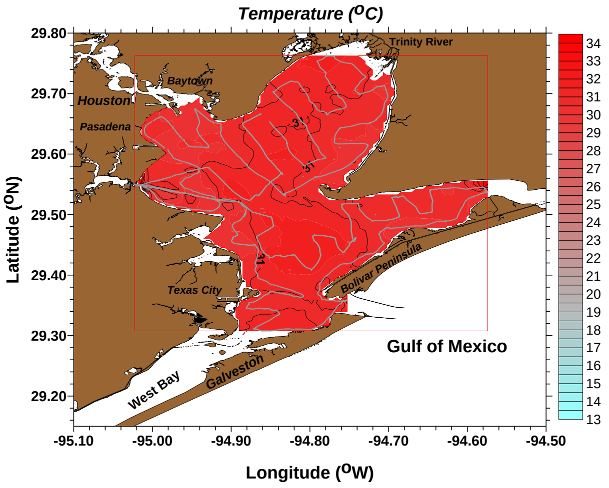

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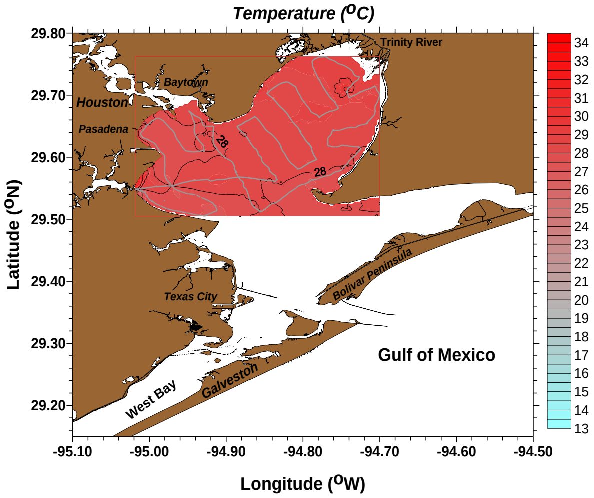

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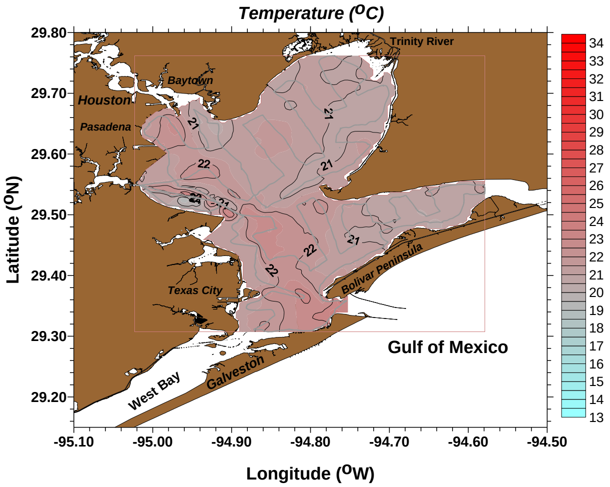

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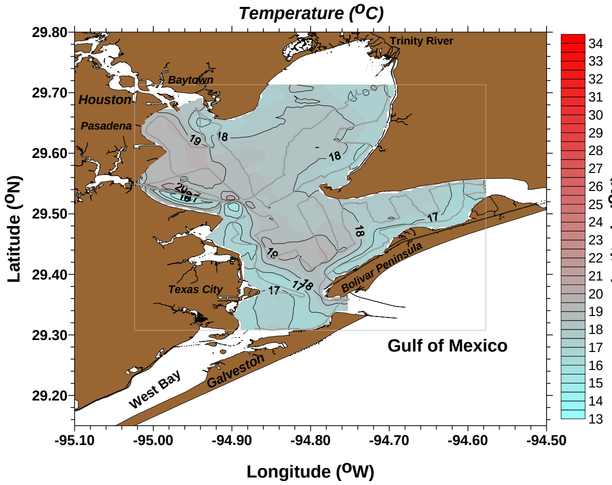

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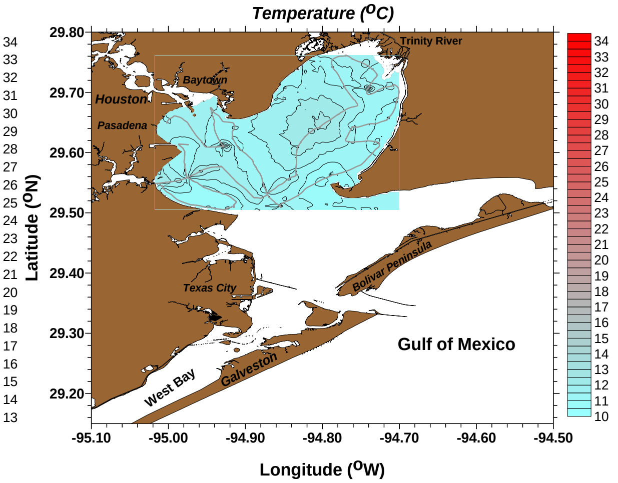
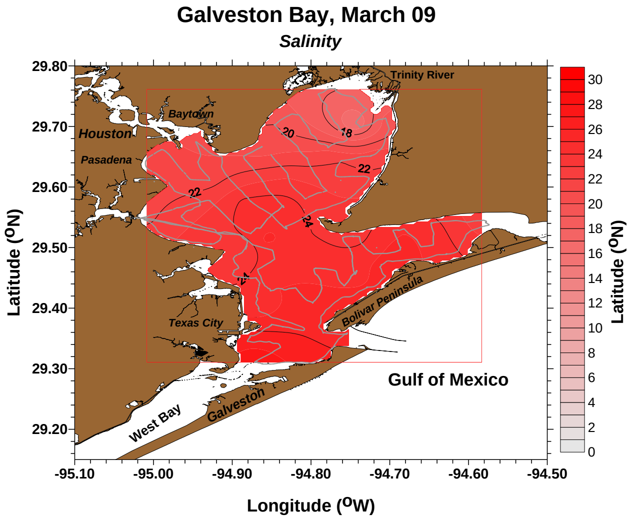


Galveston Bay, December 09

Salinity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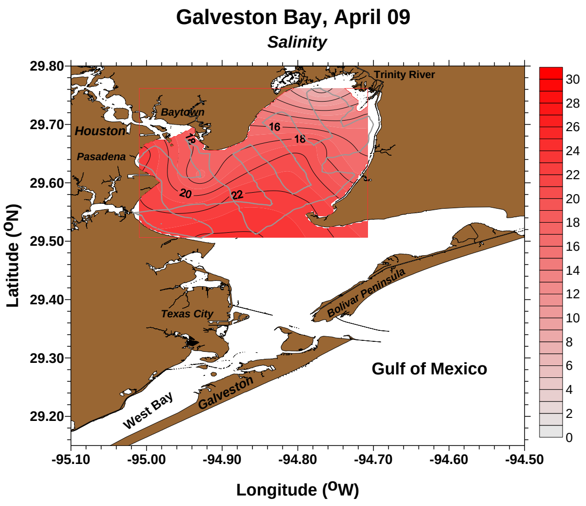
Salinity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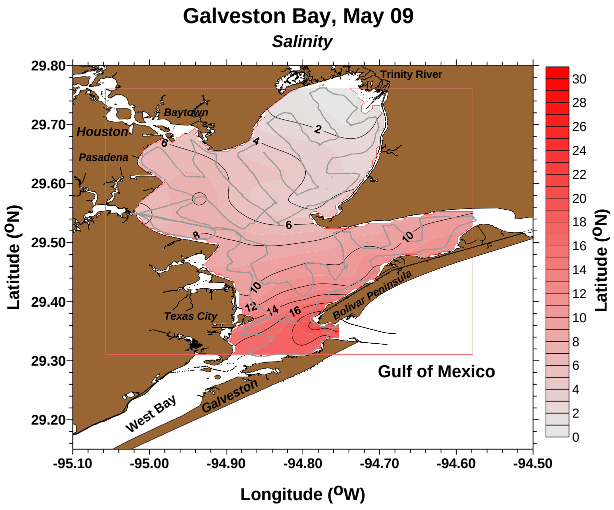
Salinity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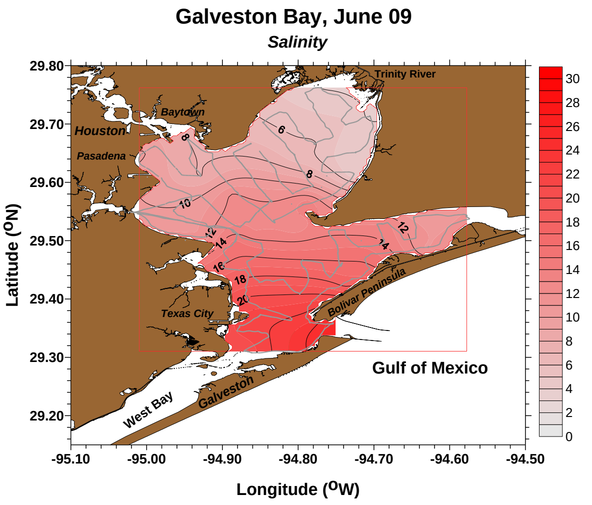
Salinity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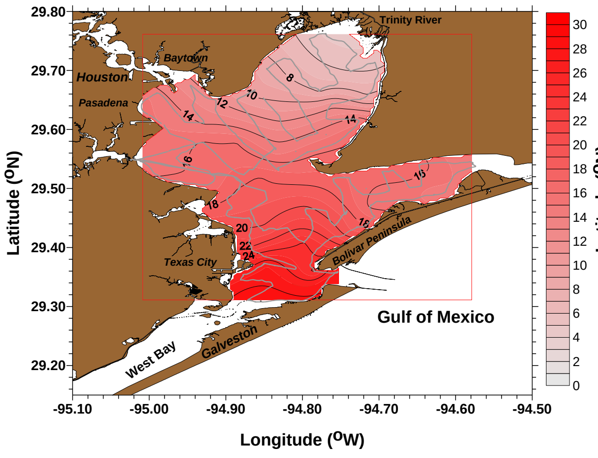
Salinity

Galveston Bay, July 09

Salinity



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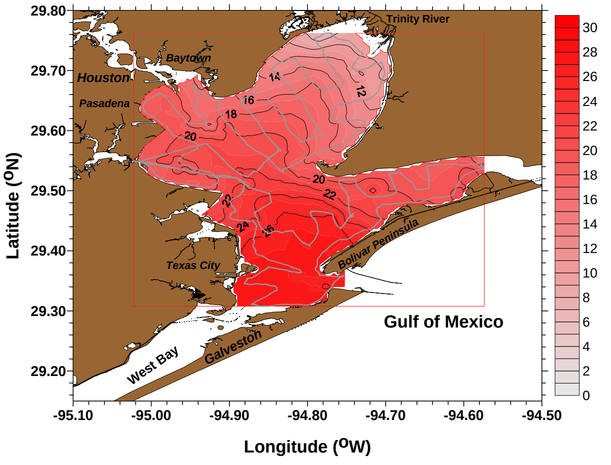
Salinity



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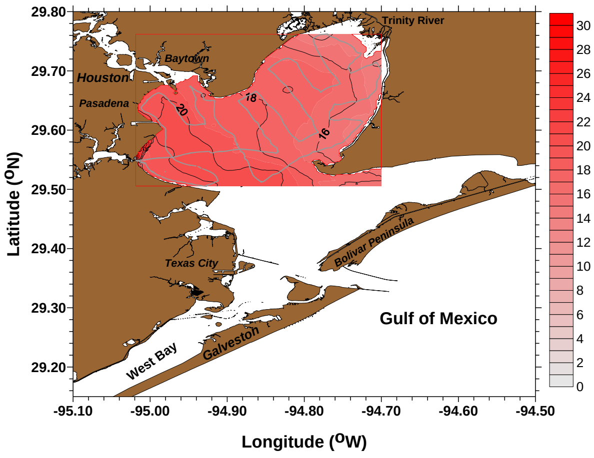

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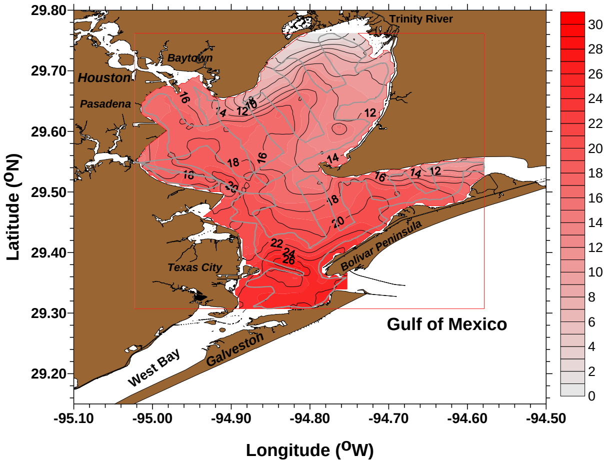

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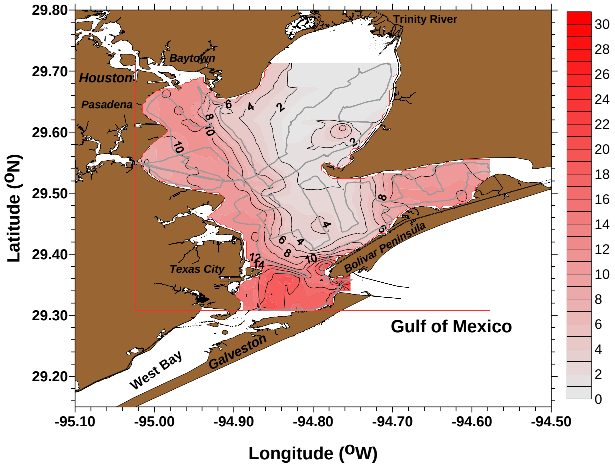
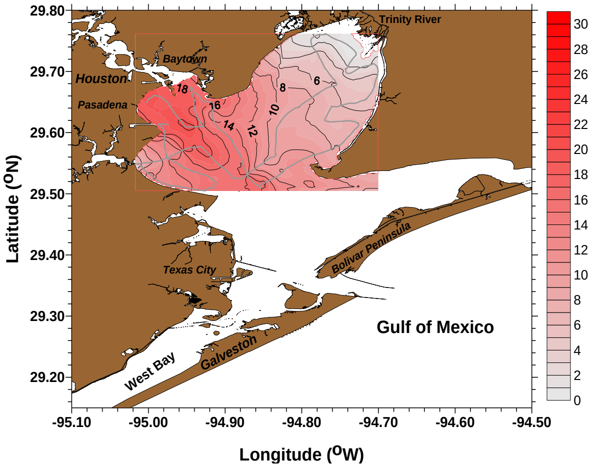
Salinity

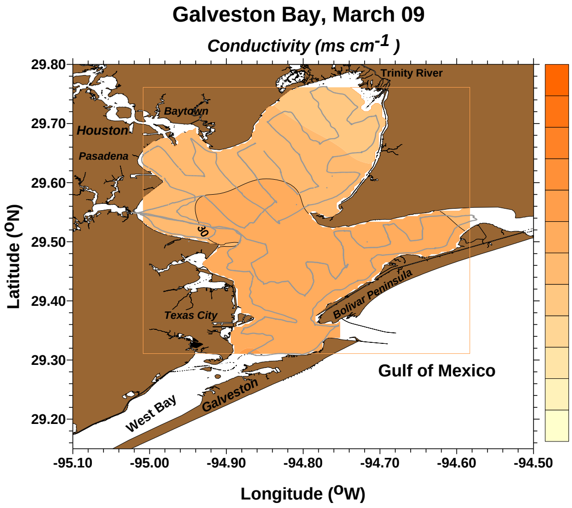


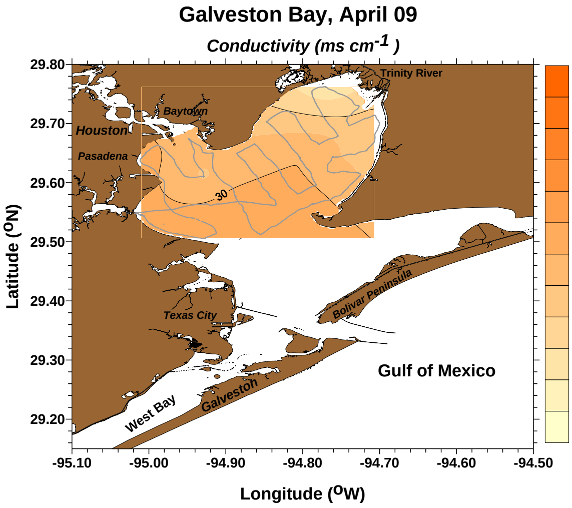
Galveston Bay, December 09

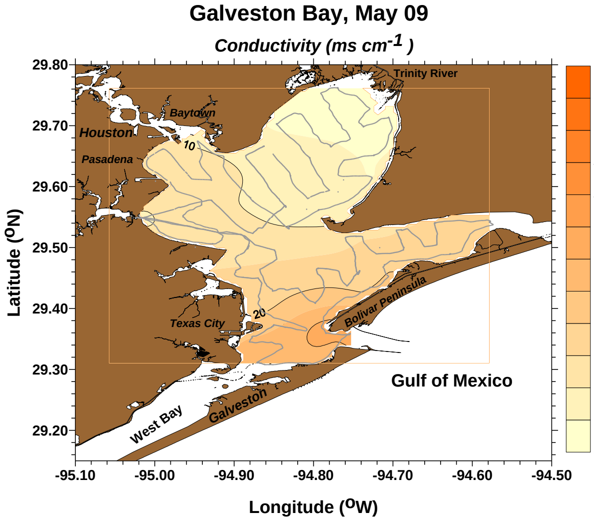
Salinity

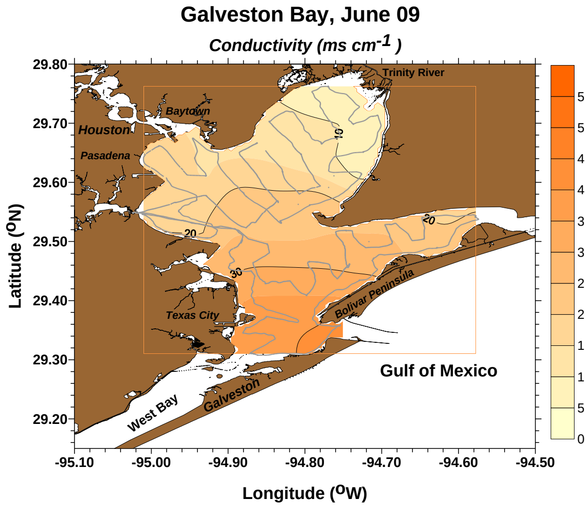


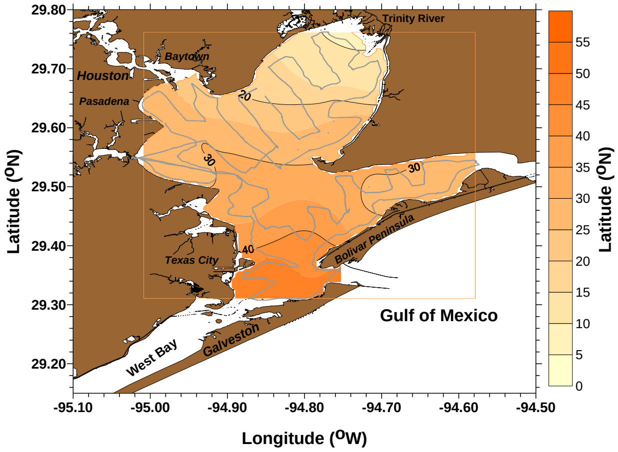
Conductivity (mS cm^{-1})





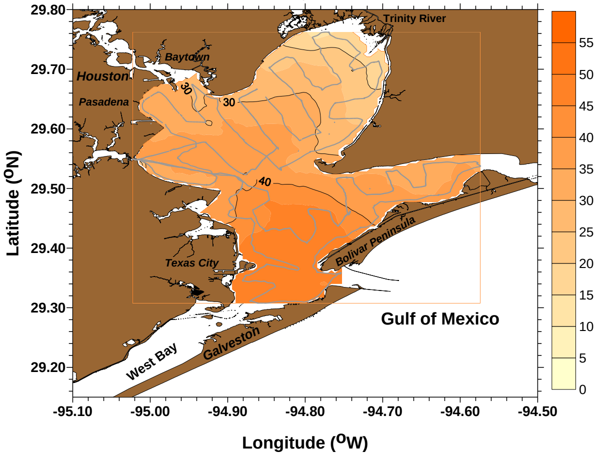






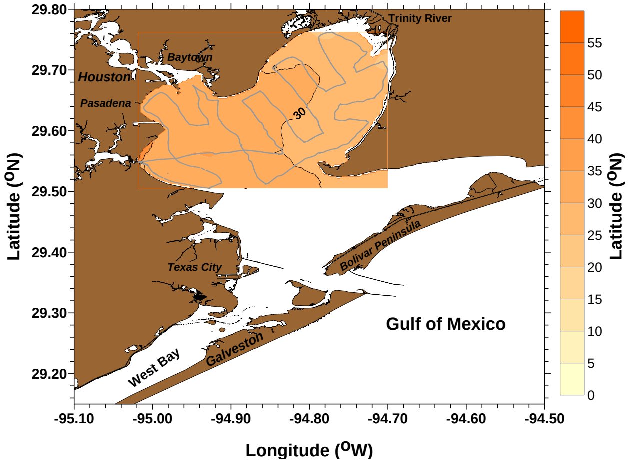
Galveston Bay, July 09

Conductivity (ms cm^{-1})



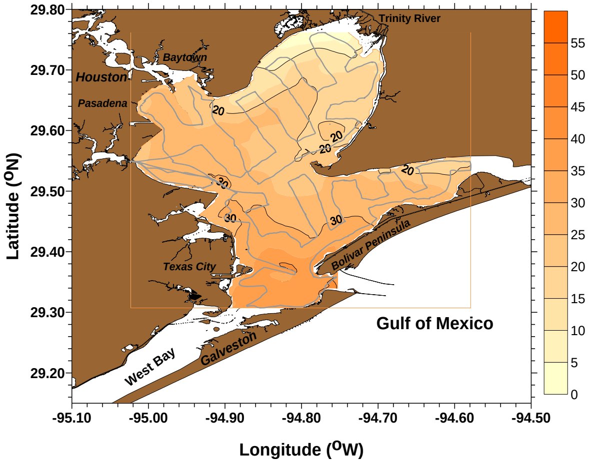
Galveston Bay, August 09

Conductivity (ms cm^{-1})



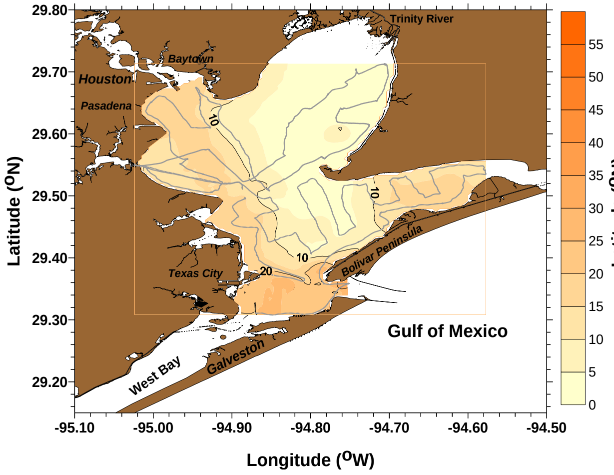
Galveston Bay, September 09

Conductivity (ms cm^{-1})



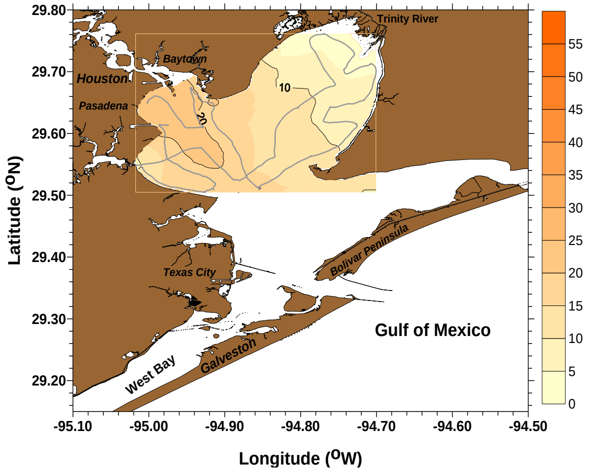
Galveston Bay, October 09

Conductivity (ms cm^{-1})



Galveston Bay, November 09

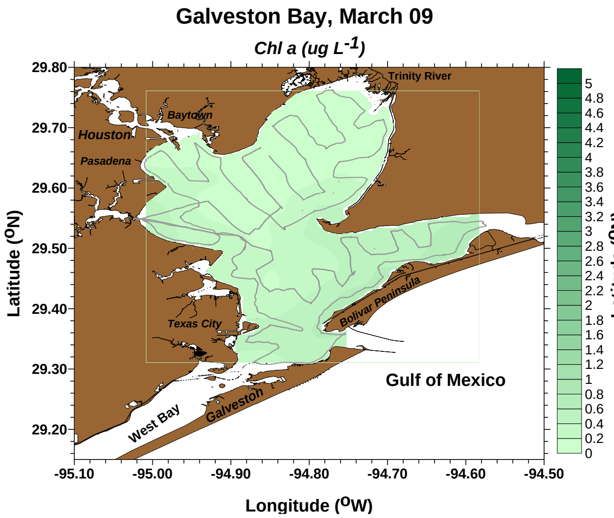
Conductivity (ms cm^{-1})

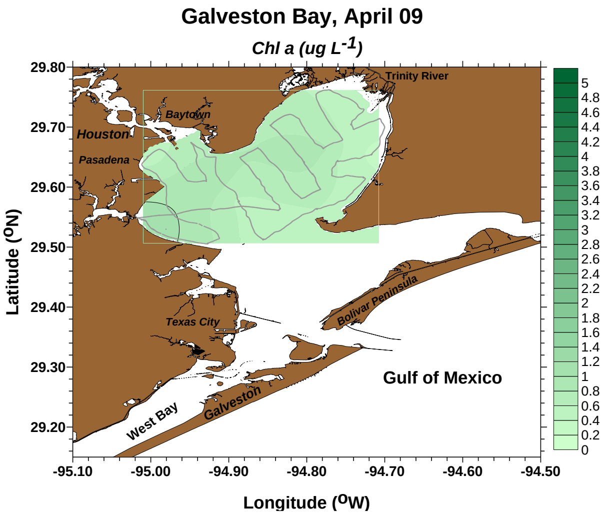


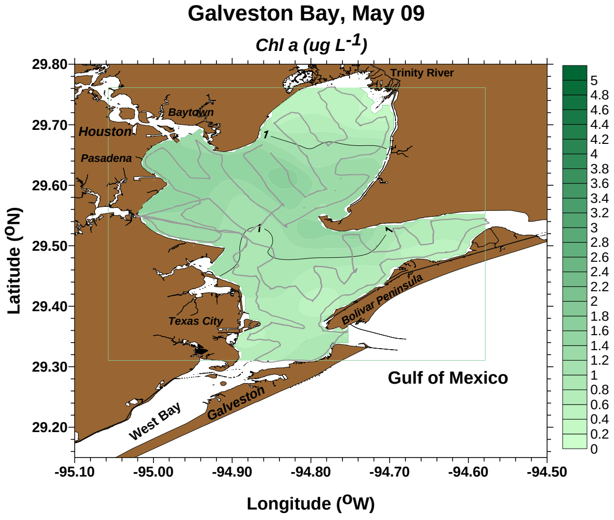
Galveston Bay, December 09

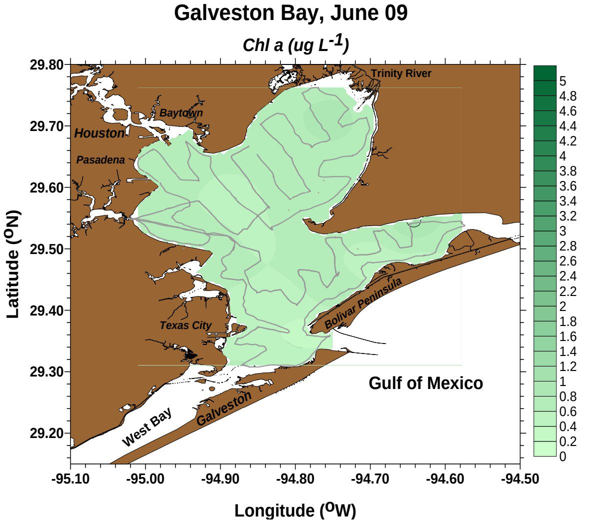
Conductivity (ms cm^{-1})

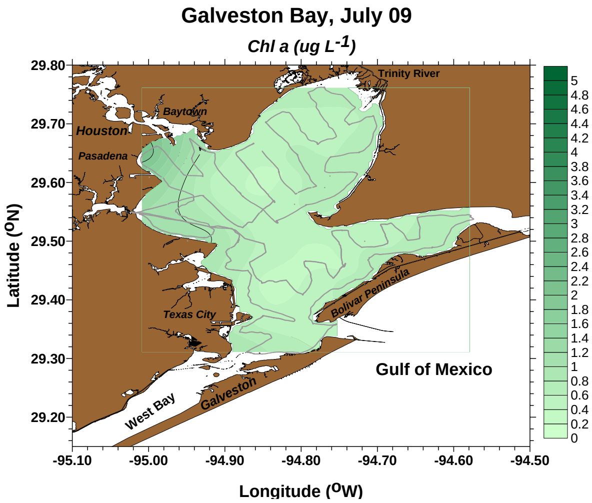
Chlorophyll (ug L^{-1})





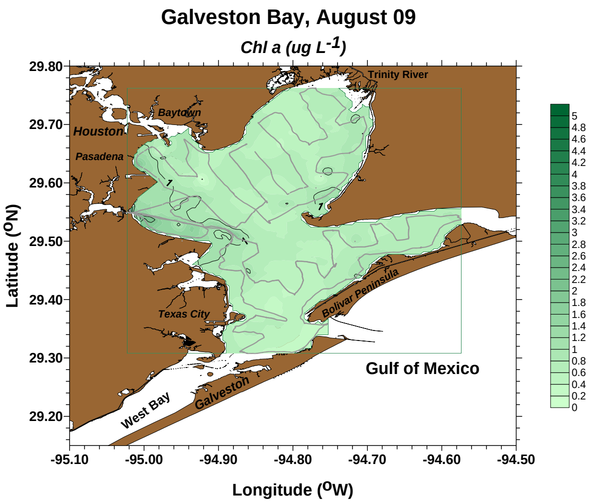






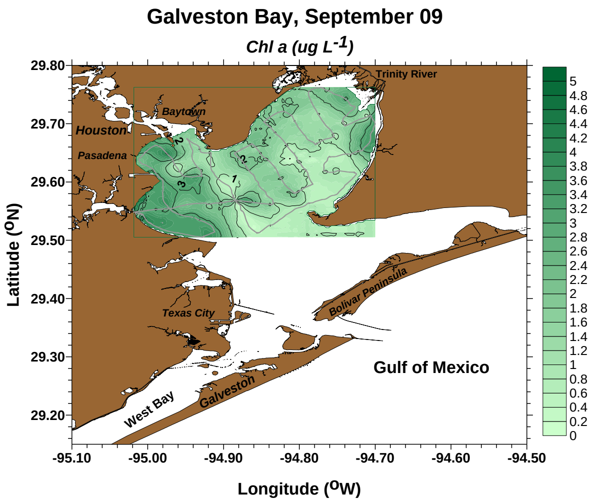
Galveston Bay, July 09

Chl a (ug L^{-1})



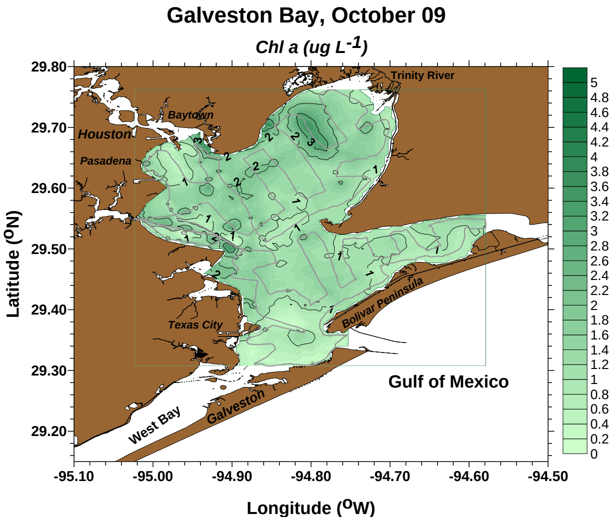
Galveston Bay, August 09

Chl a (ug L^{-1})



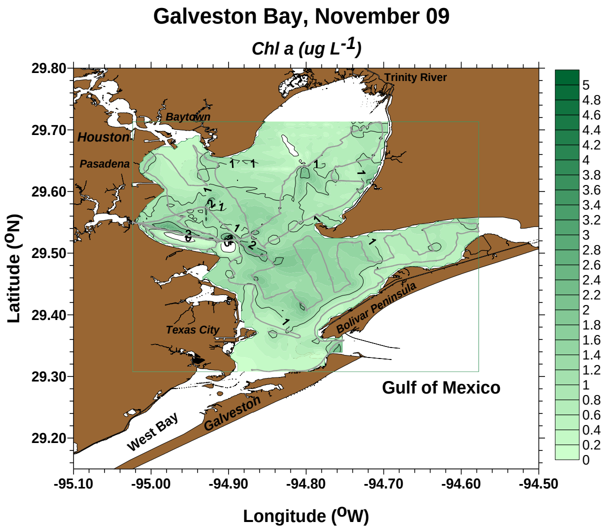
Galveston Bay, September 09

Chl a (ug L^{-1})



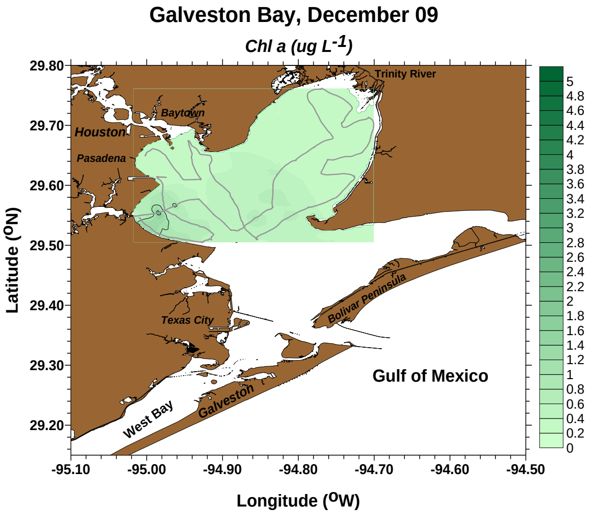
Galveston Bay, October 09

Chl a (ug L^{-1})



Galveston Bay, November 09

Chl a (ug L^{-1})

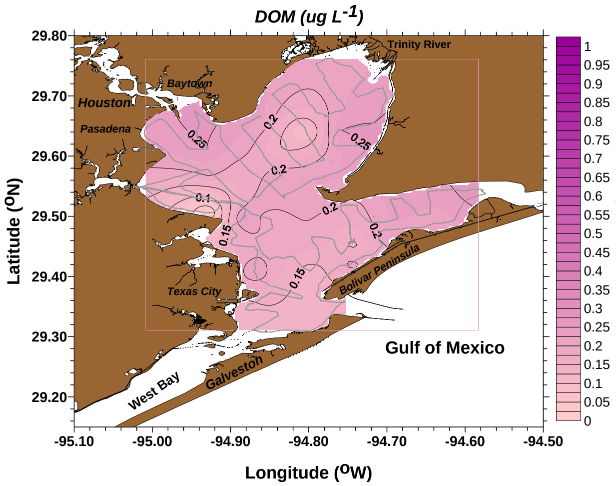


Galveston Bay, December 09

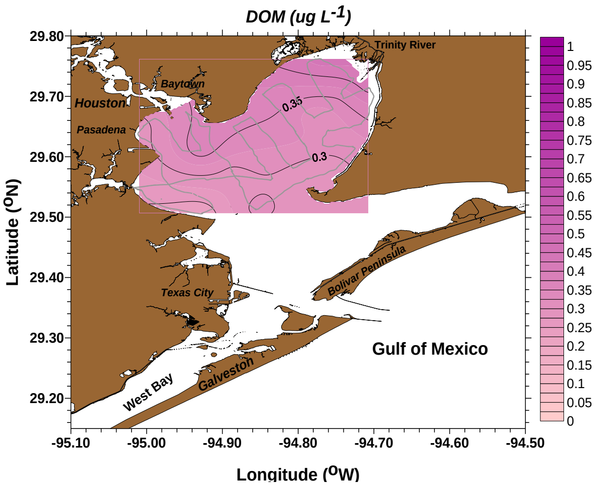
Chl a (ug L^{-1})

Dissolved organic matter (DOM) (ug L^{-1})

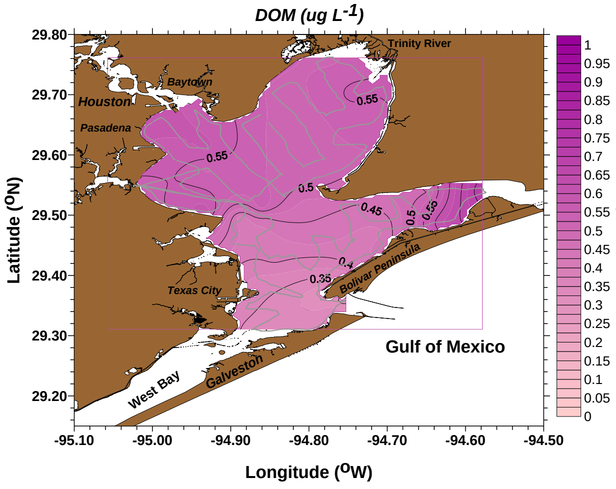
Galveston Bay, March 09



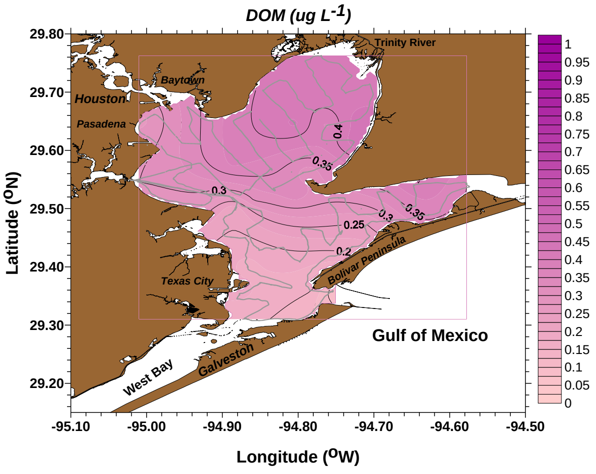
Galveston Bay, April 09

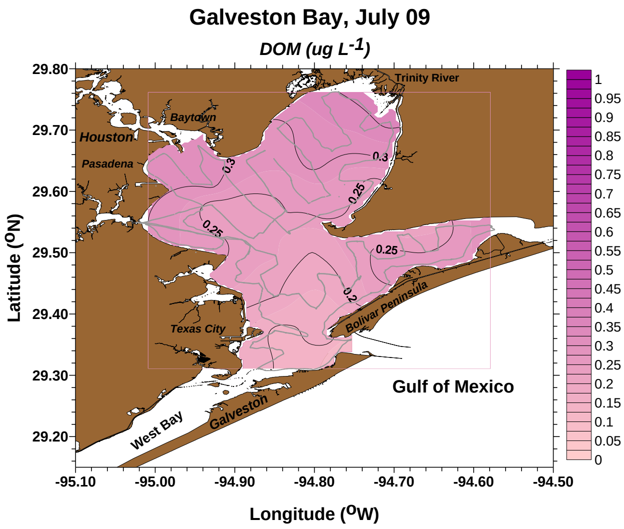


Galveston Bay, May 09

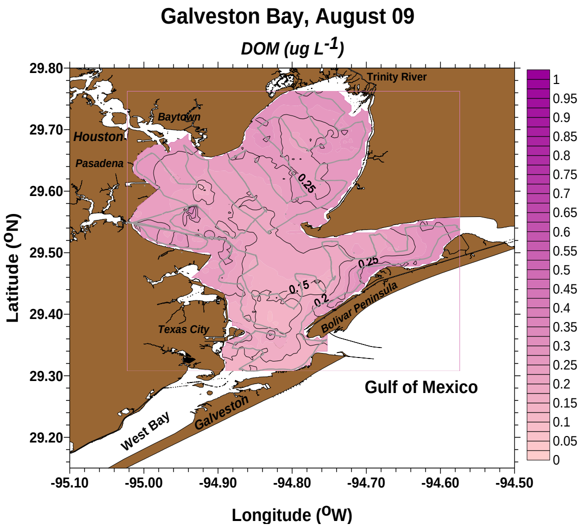


Galveston Bay, June 09

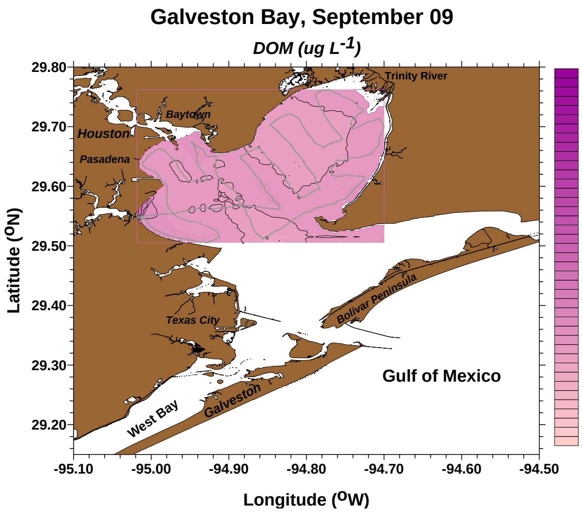



Galveston Bay, July 09

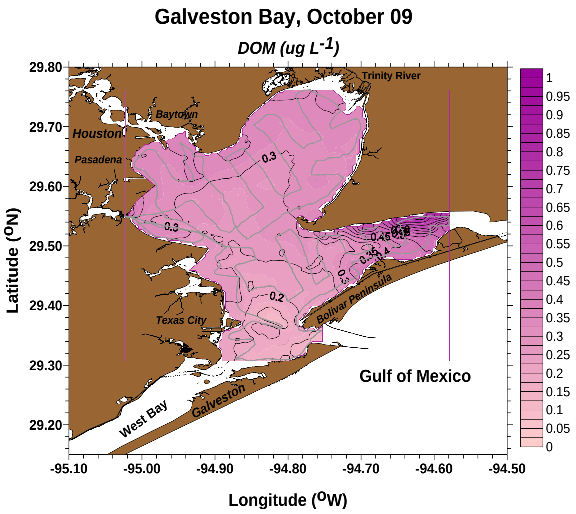
DOM (ug L^{-1})


Galveston Bay, August 09

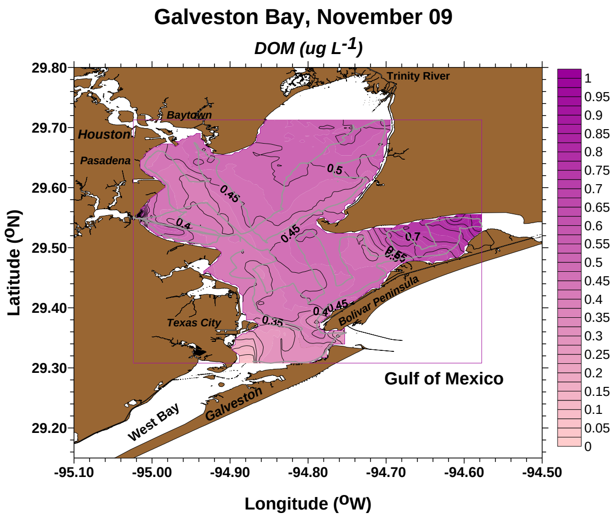
DOM (ug L^{-1})


Galveston Bay, September 09

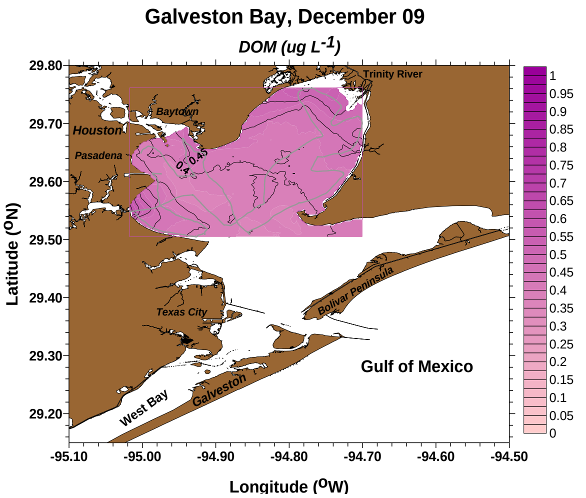
DOM (ug L^{-1})


Galveston Bay, October 09

DOM (ug L^{-1})


Galveston Bay, November 09

DOM (ug L^{-1})


Galveston Bay, December 09

DOM (ug L^{-1})