SUSPENDED SEDIMENT DYNAMICS OF TEXAS ESTUARIES

A Dissertation

by

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Anthony Sherman Reisinger

This dissertation meets the standards for scope and quality of
Texas A&M University-Corpus Christi and is hereby approved.

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ABSTRACT

Suspended sediments are an integral part of estuarine systems in that they impact water quality and form habitats; their flux is driven by the interplay between freshwater inflow, tidal currents, wind-wave resuspension, commercial fishing, and dredging operations. The objective of this dissertation is to investigate the relative importance of the aforementioned drivers of suspended sediment in the three largest Texas estuaries (Galveston, Matagorda, and Corpus Christi Bays) using a variety of analysis methods. Analyses of suspended sediment drivers using a Texas State water quality database of in situ samples (Chapter II), development of an algorithm to transform satellite imagery into suspended sediment concentrations (Chapter III), and analysis of a 12-year time series of satellite-derived suspended sediment concentrations (Chapter IV) were used to accomplish the dissertation objectives.

The relative importance of freshwater inflow, tidal currents, and wind-wave resuspension was determined by statistical analyses of in situ point measurements of total suspended solids (TSS) and environmental forcings for the period of 2000-2010. The findings from these analyses show that wind-wave resuspension is the most dominant forcing of TSS in Corpus Christi, Matagorda, and Galveston Bays. The analyses further indicated that freshwater inflow in Galveston Bay and astronomical tides in Matagorda Bay also influence the variability of TSS.

An algorithm to transform satellite reflectance data into TSS was created Analyses determined the best model was an exponential fit of a red-green band ratio. The algorithm was then used to create synoptic time series of TSS for the period of 2002-2014 for the estuaries.

Analysis of the satellite-derived time series shows how freshwater inflow, tidal currents, wind-wave resuspension, commercial fishing, and dredging operations influence the long-term variability of TSS in Galveston, Matagorda, and Corpus Christi Bays. Median and interquartile range composites of suspended sediments were generated for seasonal wind and inflow regimes in each estuary. TSS patterns show that the Galveston Bay system is dominated by riverine inflow with some influence from frontal passages. Surprisingly, the influence of oyster harvesting causing locally high TSS values in Galveston Bay is the most salient pattern within the estuary. Matagorda Bay's patterns indicate that the system is mostly controlled by wind-wave resuspension with patterns changing between northern frontal passages and southeasterlies dominated seasons. Corpus Christi Bay is similarly influenced by wind-wave resuspension with different patterns during the predominant northerlies and prevalent southeasterlies seasons. The impact of dredging is also apparent in long-term patterns of Corpus Christi Bay as concentrations of suspended sediments over dredge spoil disposal sites are higher and more variable than surrounding areas, which is most likely due to less consolidated sediments and shallower depths requiring less wave energy for sediment resuspension.

For Corpus Christi and Matagorda Bays, this research (Chapters II & IV) showed that wind-wave resuspension is the dominant forcing of TSS. Satellite data allowed the identification of patterns characteristic of different wind regimes. Additionally the point data analysis (Chapter II) showed that tidal forcing has an influence on TSS in Matagorda Bay. Both analyses (Chapters II & IV) show that wind forcing is less influential in Galveston Bay as compared to the other estuaries, and that freshwater inflow are important in Galveston Bay.

A major highlight of this research is the advantage provided by long synoptic time series of satellite-derived TSS that elucidated the major drivers of suspended sediments in estuaries as

well as their seasonal variability. With usage of satellite data, this research identified oyster harvesting to be a significant source of suspended sediment in Galveston Bay.

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DEDICATION

To Lindy, my love and light

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CHAPTER I: INTRODUCTION

1. Background & Relevance

1.1. Estuarine sediments importance

Estuaries are transitional zones where riverine systems combine with oceanic systems creating extremely dynamic environments. They exhibit characteristics of riverine and oceanic systems such as floods and droughts, as well as tides and waves [*Ward and Montague*, 1996]. Suspended sediments are an integral part of estuarine systems in that they impact water quality and form habitats; their flux is a result of interplay between freshwater inflow, tidal currents, wind-wave resuspension, commercial fishing, and dredging operations. They contribute to processes such as the formation and vertical accretion of subtidal and intertidal habitats, food web dynamics, nutrient and pollutant transport, and light attenuation [*Nichols and Biggs*, 1985; *Ward and Montague*, 1996]. Suspended sediments are indicators of water quality, ecosystem health, and important inputs to the morphodynamics of the estuarine system [*Ward and Montague*, 1996]. Studying sediments provides an insight into their effects on habitats (e.g. flats and salt and brackish marshes, submerged aquatic vegetation, and oyster reefs) both adjoining and within estuaries. The existence of these habitats is dependent upon a delicate balance between sediments and hydrodynamics. Changes to sediment dynamics of the system can cause large changes to the habitats within and adjoining the complex [*Thrush et al.*, 2004; *Ravens et al.*, 2009].

Take, for example, intertidal habitats such as salt marshes. Salt marshes require sediment input to counter the effects of relative sea-level rise and erosion. Reduction in the amounts of sediment they receive can lead to the conversion of salt marshes to open water[*Brinson et al.*, 1995; *Morris et al.*, 2002; *Ravens et al.*, 2009; *Kirwan et al.*, 2010]. When adequate amounts of sediment are supplied to salt marshes, however, they are able to keep pace with relative sea-level rise and can spread in areal extent [*Brinson et al.*, 1995; *Kirwan et al.*, 2011].

In contrast, too much suspended sediment can negatively affect the viability and distributions of subtidal habitats such as submerged aquatic vegetation (SAV) and oyster reefs [*Thrush et al.*, 2004; *Orth et al.*, 2006]. Sediment-laden water attenuates light needed for photosynthesis and directly impedes primary production of the SAVs and the phytoplankton food source of oysters. Thus, prolonged periods of turbidity created by suspended sediments are one of the primary causes of SAV and oyster reef loss worldwide[*Stanley and Sellers*, 1986; *Orth et al.*, 2006]. For oysters, excessive amounts of suspended sediments not only reduces the amount of phytoplankton they feed on, but also clog their filtering gills and cause suffocation of oysters [*Stanley and Sellers*, 1986]. These alterations ultimately reduce the amount of habitat created by these organisms and negatively affect the fauna that use these areas as nurseries.

2. Sediment Sources

There are a variety of sources and pathways through which sediments enter estuaries. They include erosion of watersheds and continental shelves, erosion of estuarine margins and bottom substrates, atmospheric deposition, biological productivity, and in-situ mineral production [*Nichols and Biggs*, 1985]. The relative abundance of one source of sediment over another is location-specific and largely controlled by first- and second- order coastal features such as coastal-tectonic setting, antecedent topography, watershed size and composition, available tidal and wave energy, and climate [*Inman and Nordstrom*, 1971]. In general, however, there are essentially two sources of sediments that enter estuaries on short time scales: terrestrial and marine. Terrestrial and marine sediments enter coastal estuaries through runoff via fluvial systems and overland flow while tidal currents drive marine inflows through inlets, sounds and overwash. Once supplied to an estuarine system they may undergo multiple cycles of transport, resuspension, erosion and sedimentation, which vary temporally at scales from seconds to decades and spatially from centimeters to kilometers depending on forcing. These cycles represent the hourly to seasonal variability of sediment dynamics within estuaries [*Nichols and Biggs*, 1985].

3. Sources of change

While considerable amounts of change can occur from day to day variability of natural processes, this is not the source of large-scale changes within estuaries. Episodic events such as storms and frontal passages can have substantial impact on estuaries[*Ward*, 1980; *Ward and Montague*, 1996]. During storms typical processes become accelerated. Erosion and transport, which would take years can occur in less than a day[*Ward and Montague*, 1996]. Large fluxes of water from storm surge currents and waves alter bathymetry resuspend and erode enormous amounts of sediment in both estuaries and on the shelf. Estuarine sediments are then exported to the nearshore or transported to different portions of the estuary. These changes can alter sediment storage and affect circulation for years to come [*Nichols and Biggs*, 1985].

On bar-built coasts, storm surge can breach barrier islands and spits opening new tidal inlets. This action can alter estuarine circulation in the short-term. However, if tidal energy can overcome wave energy and littoral sediment transport, the tidal inlet can stay open causing long-term changes to the estuary and its sediment dynamics through alteration of the hydrodynamics.

Frontal passages can move substantial amounts of water resulting in wind setup. Wind-induced currents and waves can resuspend substantial amounts of sediment and erode shorelines. As an entire estuary becomes loaded with sediment from wave resuspension, the sediment can then be exported into the oceanic system upon the emptying of the bay or transported into intertidal estuarine habitats [*Ward*, 1991].

4. Anthropogenic tailoring of coastal systems

Anthropogenic manipulations to coastal systems are now further complicating the understanding of estuarine systems [*Nichols and Biggs*, 1985; *Prandle*, 2009]. Pulses and movements of water and sediment, once seasonal, can now occur at any time, and vary in magnitude from human alterations [*Thrush et al.*, 2004]. Humans are altering the water cycle through the physical modifications of the landscape by damming of rivers and land-use changes within the watershed. These changes are accompanied by dredging and commercial fishing operations within estuaries. The subsequent changes to the natural system and estuarine processes are largely unknown.

Dams constructed in coastal watersheds have profound impacts by impounding large amounts of sediment and water within their reservoirs. These dams trap sediment and water stopping it from reaching the coast so humans can use the water for agricultural and municipal uses. Ultimately, dams reduce the amount of sediment-laden water that reaches the estuaries from the rivers [*Chen*, 2005]. In contrast, when episodic precipitation events fill reservoirs over their capacity, large amounts of water are released. This is done in an effort to avoid extensive flooding. Water released from the reservoirs then erodes downstream riverine systems. Coastal environments within estuaries are then flooded by a large pulse of water and sediment (see Figure I-1). These pulses of sediment-laden water negatively impact SAVs and oyster reefs causing change in the loss or degradation of these estuarine communities [*Orth et al.*, 2006]

Other sources of sediment that impact estuarine environments come as a result of dredging and commercial fishing operations also release large amounts of sediments within estuaries by resuspending sediments that were once buried within sub- and inter- tidal habitats [*Schubel et al.*, 1979; *Dellapenna et al.*, 2006]. Newly suspended sediments have the potential to affect habitats, depending on the length and location of these dredging and fishing operations. Schubel et al.[1979] found that the yearly average of the total amount of sediment resuspended by commercial shrimping within Corpus Christi Bay was 10-100 times more than that caused by maintenance dredging. Moreover, dredging does not only have short-term impacts, the physical alterations made to estuaries through the creation of navigation channels change estuarine hydrodynamics by design and subsequently alter sediment flux [*Bruun*, 2005; *Prandle*, 2009]. These changes can cause unintended consequences to coastal habitats by increasing or decreasing erosion and by altering physiochemical properties of estuarine waters in which habitats develop.

5. Methods of measuring suspended sediment

5.1. Traditional in-situ measurements

There is a variety of ways to measure suspended sediment. Typically, suspended sediments concentrations are quantified by measuring total suspended solids (TSS). This measurement involves taking a volume of water from a point within an estuary and passing through a pre-weighed glass fiber filter [*Texas Commission on Environmental Quality*, 2008]. The filter is then dried and weighed with the mass of the sample divided by the volume of water filtered, normally, denoted in mg/l. For temporal studies of estuaries, the sampling is then repeated at the same station over time, thus providing insight into the processes ongoing in the area. Sampling multiple points within an estuary becomes arduous and time-consuming as the number of stations increases with the expanse of the water body studied [*Ward and Montague*, 1996]. Most

State and Federal agencies use a few point measurements within estuarine systems to characterize the overall condition of the system [*Ward and Montague*, 1996; *Texas Commission on Environmental Quality*, 2008]. These measurements are not only costly, but also are biased by sampling logistics. Boats are mostly deployed when weather conditions are fair. Thus, samples are biased to fair weather conditions. While these measurements provide much-needed data, their lack of spatial and temporal coverage creates impediments when trying to characterize the complexity and heterogeneity of an estuarine system. Estuaries are highly dynamic environments and the conditions observed at a single point can be the result many complex and interrelated processes. Thus, the observations may not reflect the system in space or throughout time [*Ward and Montague*, 1996]

5.2.Advances in monitoring

In the late 1970's advances in sediment monitoring allowed the spatial gap caused by traditional sampling to be filled with the use of helicopters [*Shideler*, 1984]. Using a US Coast Guard helicopter rather than a boat, Shideler [1984] Corpus Christi Bay was able to sample 14 points throughout the Corpus Christi Bay within five hours producing some of the first quasi-synoptic measurements of suspended sediments in this region. He repeated this sampling methodology a total of eight times and was able to characterize the dominant spatial patterns of suspended sediment distributions, and characterize the bays response to wind-wave resuspension from prevalent frontal passages and predominant southeasterlies. More advances in the monitoring of suspended sediments came when Stumpf and Peanock [1989] discovered that weather satellites were able to quantify suspended sediments. Their work ushered the usage of satellite remote sensing in the monitoring of suspended sediments and provided synoptic views of suspended sediment dynamics. The usage of these satellites allowed for the creation of some of the first long-term synoptic time series, also known as Environmental Data Records (EDR). EDRs of suspended sediments spanning decades with data collected daily [*Stumpf and Pennock*, 1989; *Ruhl et al.*, 2001]

In recent years, satellites have been used to monitor suspended sediment and other water quality parameters such as chlorophyll-a (CHL-a) and colored dissolved organic matter (CDOM) [*Matthews*, 2011]. Most of the research has focused on oceanic areas [*McClain*, 2009]. However, there is now a movement to study estuaries and coastal areas using satellites [*Miller and McKee*, 2004; *Doxaran et al.*, 2009; *Chen et al.*, 2010; *Petus et al.*, 2010; *Loisel et al.*, 2014; *Feng et al.*, 2014]. Depending on a satellite's orbit, spectral resolution, and spatial resolution, coastal regions can be covered daily and provide a better understanding of the dynamics and variability of their waters. Overflights from polar-orbiting satellites carrying National Aeronautics and Space Administration's (NASA)'s Moderate-Resolution Imaging Spectroradiometer (MODIS) provide two almost-daily images of estuaries and coastal areas see (Figure I-1). The MODIS sensor onboard NASA's Aqua satellite has been in orbit since 2002. MODIS was designed with 36 spectral channels to support observations of oceans, land, and clouds [*McClain*, 2009]. There are nine 1-km bands that were designed for ocean color observations in the visible to near-infrared (NIR) (412-816 nm) portion of the electromagnetic spectrum. Over turbid waters of inland and coastal areas, however, the dynamic range of the sensor can be exceeded, leaving the actual ocean color signal to be unknown [*Franz et al.*, 2006]. Many researchers are now using land/cloud bands to quantify suspended sediment concentrations in coastal waters (e.g. [*Miller and McKee*, 2004; *Doxaran et al.*, 2009; *Chen et al.*, 2010; *Petus et al.*, 2010; *Loisel et al.*, 2014; *Feng et al.*, 2014]). These bands are less sensitive than the 1-km ocean color bands, have broader dynamic ranges and do not suffer from the problems of the higher resolution ocean color bands [*Franz et al.*, 2006]. The land (1,2) and cloud bands (3-9) have spatial resolutions of 250 and 500 meters, respectively. Band 1 is optimal for detecting suspended sediment due to high reflectance from sediment in the water column around the red portion of the spectrum centered at 645 nm. Using the red portion of the spectrum, quantifying suspended sediments has little impact from phytoplankton pigments, such as CHL-a, in low concentrations [*Bukata*, 1995]. Yet, in high concentrations of phytoplankton (CHL-a > 30mg/l), the red portion of the signal can be influenced and the strength of reflectance of suspended sediments reduced [*Ritchie and Zimba*, 2006].

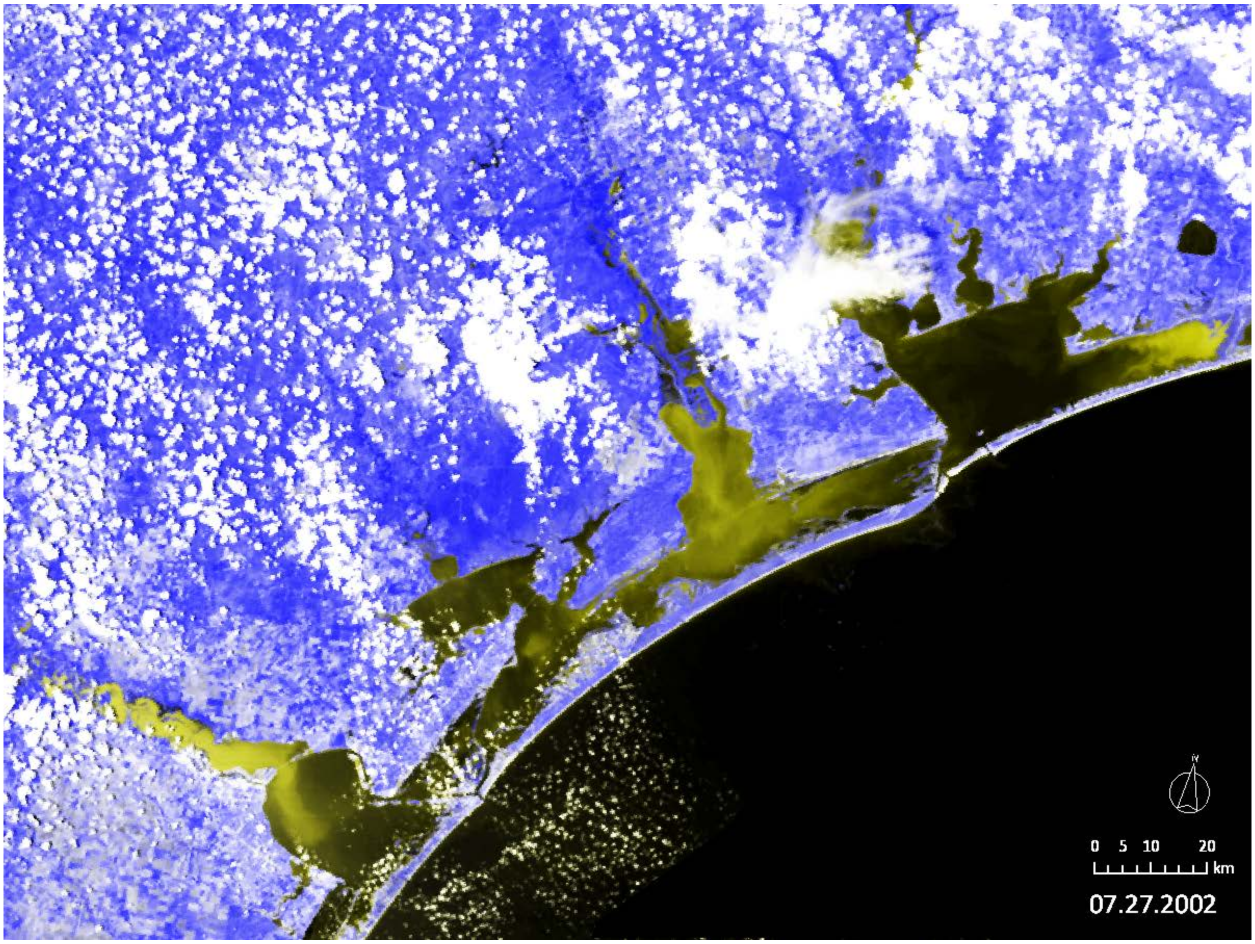

Figure I-1: False-color image from MODIS sensor on Terra at 250-meter resolution. False color image created using a band combination of 1,1,2 the yellow color represents suspended sediments flowing into the estuaries after a flooding event.

5.3.Challenges using satellites

Quantification of sediments from space is particularly challenging in coastal areas due to the large amount of atmospheric aerosols and the multitude of constituents in the water [see Martin, 2004 and Kirk, 2010]. Atmospheric corrections must be performed so not to estimate constituents of the atmosphere as part of those in the water. Methods to atmospherically correct in Case II waters, such as Wang & Gordon [1994] and Stumpf et al. [2003], routinely fail in coastal areas. In Case II waters with high loads of sediment, atmospheric corrections routinely used for MODIS sensors assume highly turbid aerosols and subtract too much from the reflectance signal and often result in negative reflectance [*Acker et al*., 2006]. Another problem in coastal waters has to do with the scattering of light with increasing suspended sediment concentrations. As sediment concentration increases, reflectance of the red portion of the visible spectrum shows up in the longer NIR wavelengths [*Martin*, 2004]. The expansion into NIR contaminates the part of the spectrum used to remove atmospheric aerosols and is one of the largest sources of error associated with atmospheric corrections [*Werdell et al*., 2009]. These problems can introduce large errors in the creation of long-term time series of ocean color products.

More recently, MODIS land data products have been used to quantify suspended sediments in coastal estuaries with high-resolution, 250-meter and 500-meter, MODIS data [Doxaran et al. 2011, *Yang et al.* 2009,]. Doxaran et al. [2011] used the MYD09 and its counterpart MOD09 to quantify suspended sediments accurately in the Gironde estuary, France. They accomplished this using a remote sensing reflectance (*Rrs*) ratio algorithm of Bands 1-2, red and near-infrared, respectively. In their study, they found that the atmospheric correction used by the land data community is sufficient to quantify suspended sediments ranging from 77–2182 g/m^3.

Remote sensing of suspended sediments is further complicated by problems associated with the satellites and their sensors. Considerable problems arise, such as spectral and spatial resolution, geolocation, land contamination, bottom contamination, sun glint, sensor calibration, and sensor drift [see *Martin*, 2014].

5.4. Quantification of sediments from space

Despite the aforementioned problems, estimation of suspended sediment from satellites is possible. Many researchers use MODIS and other satellites to understand coastal and oceanic sedimentary processes [see *Acker et al.*, 2005]. Principally, there are two methods used for estimating suspended sediment concentrations from remotely sensed satellite data: semi-analytical algorithms and empirical algorithms [see *Acker et al.*, 2005; *D'sa and Miller*, 2005]. Both methods, however, require adequate atmospheric corrections.

Semi-analytical algorithms are based on modeling of inherent optical properties (IOPs), i.e. scattering and absorption relationships of the waters constituents such as colored dissolved organic matter, chlorophyll-a, and suspended sediments. Semi-analytical algorithms relate or derive apparent optical properties (AOPs) (i.e. diffuse attenuation coefficient for downwelling irradiance and remote sensed reflectance) from mathematical relations with in-situ data [*D'sa and Miller*, 2005]. These algorithms can be overly simplistic or extremely complex. The reader is referred to D'sa and Miller, [2005] and the references within for a detailed description of these methods. It is pertinent to note however, that many researchers use these methods to obtain suspended sediment concentrations from satellite data.

Empirical algorithms relate remote-sensed reflectance (*Rrs*) of surface waters to in-situ measurements of suspended sediment or their proxies. These relationships are derived by using different types of regression techniques where statistically derived relationships between inputs (reflectance), and outputs (in-situ data) are created. Some commonly used methods employ regression techniques using signal bands, band ratios, or band mixtures of remote-sensed reflectance data [*D'sa and Miller*, 2005]

Overall, the use of satellites offers an opportunity to develop long-term data records of suspended sediments within estuaries. Satellite data can fill spatial and temporal gaps in historical, in-situ data sets allowing the distributions and concentrations of suspended sediments under varying climatological and hydrodynamic conditions such as frontal passages, floods, tropical storms, and periods of drought to be assessed. Coupling long-term data records of suspended sediment with environmental data can provide insight into the dynamics of suspended sediments within estuaries.

6. Purpose

The primary objective of this research is to determine how suspended sediments in the shallow-water estuaries of Texas respond spatially and temporally to climatological and hydrological dynamics for the time period of 2000 to 2014. This was accomplished using two different approaches. In the first approach a statistical analysis was used to analyze suspended sediment concentrations collected by the Texas Commission on Environmental Quality (TCEQ). The second method combines TCEQ measurements and satellite imagery to create an EDR for the three main Texas estuaries.

The research answers the following questions:

1. What are the dominant forcing(s) of suspended sediments in Texas estuaries?
2. How does the relative importance of fluvial, marine, and meteorological forcing of suspended sediment concentrations vary among Texas estuaries?
3. Can the temporal variability of suspended sediment concentrations be explained by the climate gradient?

4. Are commercial shrimping and dredging activities important drivers of suspended sediment concentrations?

7. Organization of the manuscript

The dissertation is organized into five chapters. Chapter I, this chapter, is an introduction to estuarine suspended sediment dynamics. The chapter also describes the objectives of the research and study sites. Chapter II is a statistical analysis of in situ measurements collected by the Texas Commission on Environmental Quality that determines the relative importance of the natural forcing of suspended sediments. Chapter III uses the in situ data and satellite data to create an algorithm that predicts daily suspended sediment concentration from 2002 to 2014 creating a suspended sediment EDR. Chapter IV uses the EDR to look at the relative importance of the forcing of suspended sediments from satellite data. Composite satellite imagery is used to highlight the different patterns related with different wind and inflow regimes. Chapter V draws broad conclusions from Chapter II-IV and summarizes the dissertation.

8. Study sites

8.1. Texas estuaries

This study focuses on the three largest estuarine systems in Texas: Galveston, Matagorda, and Corpus Christi Bays (Figure I-2). The estuaries were chosen because of their size relative to the satellites resolution and location along the Texas climate gradient. Formation of these estuaries is the result of the infilling of Pleistocene river valleys during Holocene sea-level rise [*Davis*, 2011]. They are prime examples of “bar built” estuaries described by Schubel [1971], and are separated from the Gulf of Mexico by a thin strip of barrier islands and spits (Figure I-2). Small tidal inlets, the majority of which are jettied, connect the estuaries to the Gulf. These estuaries are in a microtidal (0.6 m Gulf tide range), wave-dominated mixed energy coastal setting, and are affected by a climatic gradient with wetter conditions to the north and drier to the south [*McKee and Baskaran*, 1999; *Montagna et al.*, 2012]. As a result, average-annual freshwater inflow, normalized by bay volume, decreases 10 fold from north to south. Influence of the Texas climate gradient on freshwater inflows subsequently affects fluvial sediment input to these estuaries. Freshwater inflow into these estuaries carries large amounts of sediments during high-flow events, which is evident in their bayhead deltas. Marsh vertical accretion rates and Holocene sediment thicknesses decrease on the bayhead deltas from the Galveston Bay system to the Corpus Christi Bay system [*White et al.*, 2002] This trend indicates that suspended sediment loads carried by rivers decrease from north to south and that freshwater inflow may be relatively more important in the northern estuaries when compared to other inputs of sediments. For all bays, marine sediment input is thought to be relatively small owing to the microtidal setting of all the bays [*Yeager et al.*, 2006]

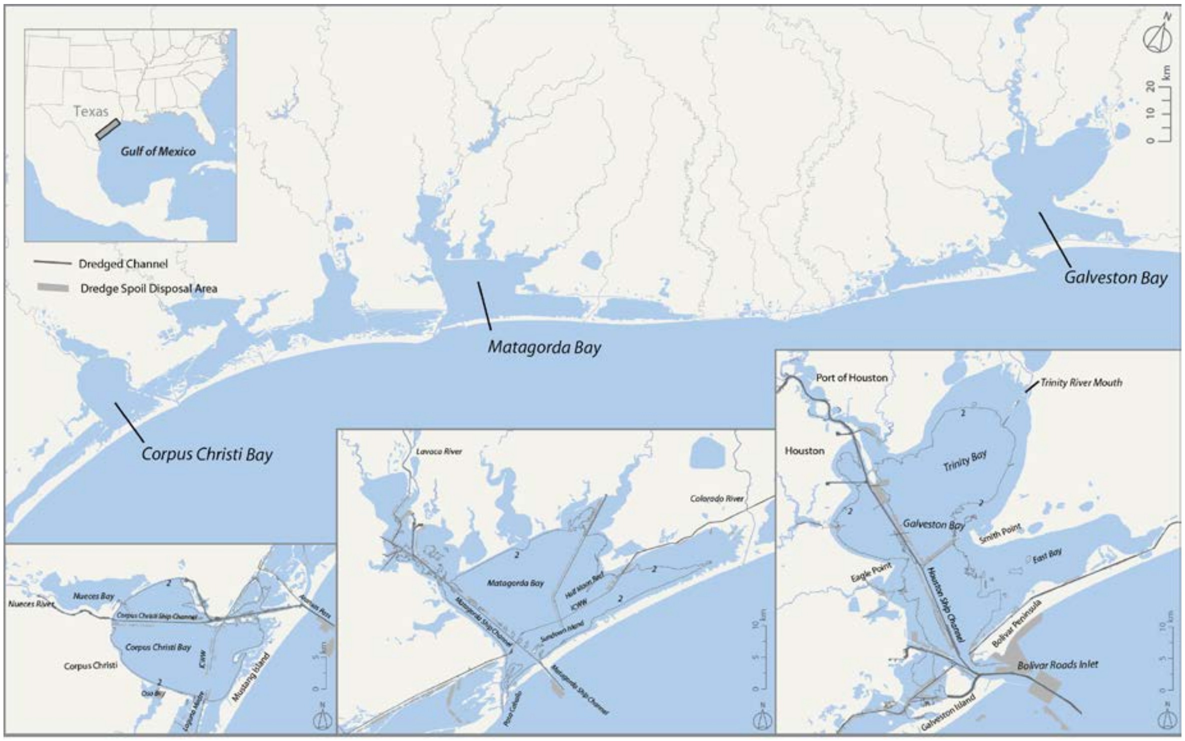

Figure I-2: Map depicting major estuaries of Texas and the river systems.

These shallow-water bodies (2-4 meters) are heavily influenced by wind [*McKee and Baskaran*, 1999]. Wind on the Texas Coast is seasonal with predominate southeasterly wind occurring from March through August and north-northeasterly from November through February [*Morton and McGowen*, 1980].

8.2.Galveston Bay

The Galveston Bay estuarine system covers an area of 1416 km^2 and consists of East, Galveston and Trinity Bays, and Trinity and San Jacinto Rivers, and other tributaries. The system connects to the GOM via the Bolivar Roads, and Rollover Pass tidal inlets. Primary inflows into the system are from the Trinity River. The entire complex varies in depth depending on location; however, the average depth is about 2.4 meters and the average tide range is 34 cm (Table I-1).

Median wind speed is 5.2 m/s coming from the southeast. During frontal passages, it has been observed that as much as half of the volume of Galveston bay can be evacuated. This is likely due to the geometry of the estuary and the position of the Bolivar Roads inlet with respect to the north wind [*Ward*, 1991]. While this bay major river system is dammed, White et al. [2002] and Phillips [*Phillips and Slattery*, 2008] found that the creation of Lake Livingston had no effect on the transport of sediment to the Galveston Bay estuarine system.

8.3.Matagorda Bay

The Matagorda Bay estuarine system covers 1158 km^2 and consists of the Colorado, Lavaca and Navidad Rivers, Tres Palacios Creek and other tributaries, Lavaca and Matagorda Bay, and other secondary embayments. The primary inflow into the system is from the Colorado River that flows into Matagorda Bay. Matagorda Bay is 3 meters in depth on average with a tide range of 17 cm (Table I-1). It is connected to the Gulf of Mexico by the two tidal inlets Matagorda Ship Channel and Paso Caballo. Median wind speed is 5.7 m/s coming from the southeast (Table I-1).

8.4.Corpus Christ Bay

The Corpus Christi Bay estuarine system covers 433 km^2 and is composed of a primary and two secondary bays, Corpus Christi and Nueces, and Oso Bays, respectively. The estuarine system receives inflow from the Nueces River and several creeks. Corpus Christi Bay is the smallest in terms of area yet it is the deepest bay on the Texas Coast averaging 4 meters in depth with an average tide range of 10 cm [*Ward*, 1997]. It is connected to the Gulf of Mexico by two tidal inlets; Packery Channel and Aransas Pass. Median wind speed from the southeast is 6.2 m/s. The majority of freshwater inflow comes in through Nueces River and flows into Nueces Bay [*Ockerman and Heitmuller*, 2010]. Shideler [1984] found that during times of high inflow, high suspended sediment concentrations in Nueces Bay did enter into Corpus Christi Bay. However, when strong wind was blowing for a prolonged period from the north substantial amounts of sediment were resuspended and spilled into Corpus Christi Bay from Nueces Bay. He hypothesized that Nueces Bay is a fluvial sediment storage basin having a control valve that allows for release into Corpus Christi Bay that is activated by strong northerly wind.

Table I-1: Physical measurements compared among Texas estuaries. Listed from north to south: from the average depth, area, volume, average annual precipitation [1951-1980; Larkin and Bomar 1983], average annual freshwater inflow (1941-1999; Texas Water Development Board, http://www.twdb.state.tx.us/data/bays_estuaries/bays_estuary_toc.htm, median wind speed and direction NCEP and tide range from TCOON, http://lighthouse.tamucc.edu/TCOON/HomePage

	Average Depth (m)	Area (km^2)	Volume (km^3)	Tide Range (m)	Rainfall (cm y^{-1})	Inflow (10^6 m^3 y^{-1})	Median Wind Speed (m/s)	Median Wind Direction (degrees)
Galveston Bay	2.4	1,416	0.088	0.32	112	14,000	5.2	141
Matagorda Bay	3.4	1,158	0.075	0.23	102	3,801	5.7	140
Corpus Christi Bay	4.0	433	0.049	0.17	76	298	6.2	135

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CHAPTER II: SUSPENDED SEDIMENT VARIABILITY IN TEXAS ESTUARIES: RELATIVE IMPORTANCE OF WIND, INFLOW AND TIDES

1. Introduction

1.1. World sediment issues and dewatering

The altering of Earth's landscapes and water cycle caused by changes in climate and human systems are having substantial impacts on coastal areas, especially estuaries. Estuarine systems are being impacted by dewatering, principally caused by human alteration of watersheds and river flows, and climatological changes in precipitation patterns [*Montagna et al.*, 2011, 2012]. Alterations to rivers by the creation of reservoirs and channel diversions divert freshwater away from estuaries for agricultural, industrial and municipal water supplies. Regional changes in precipitation patterns impact delivery of freshwater to these systems[*Montagna et al.*, 2007]. Freshwater inflow is important to the health of estuarine environments and the dewatering of estuaries will cause changes to the biological and geological components of estuarine systems. In particular dewatering has the potential to disrupt estuarine sedimentary processes.

Suspended sediments carried to estuaries by freshwater inflow, ocean exchange, and resuspension by waves are an integral part of estuarine systems. They contribute to processes such as the formation and vertical accretion of subtidal and intertidal habitats, food web dynamics, nutrient and pollutant transport, and light penetration [*Nichols and Biggs*, 1985; *Ward and Montague*, 1996].

1.2. Texas example

On the coastal plain of Texas bordering the northwestern Gulf of Mexico (GOM) (Figure I-2) the dewatering of estuaries is impacting estuarine sedimentary process, cycles and habitats. McKee and Baskaran [1999] showed that freshwater inflow and wind-wave resuspension are the dominant sedimentary processes in these estuaries. Fine-grained clay and silt are carried by freshwater inflow into the primary bay, and are then deposited in intertidal and subtidal habitats such as marshes and the open-bay bottom. These sediments are continually eroded from the bays muddy bottoms by wind-waves and associated currents. Sediments are either redeposited in the same area or transported to other portions of the bay such as intertidal habitats. While in suspension, either from freshwater inflow events or resuspended by wind-waves, sediments can also be exported to the Gulf of Mexico via inlets by tidal fluxes. While these processes control the variability of estuarine suspended sediment concentrations, the processes occur at different time and length scales, and their influence differs in magnitude among the estuaries. No studies have attempted however to compare the relative importance of these processes among estuaries although some anecdotal evidence exists in depositional environments within and surrounding the bays [*White et al.*, 2002]

For example, freshwater inflow influence on suspended sediment concentrations in Texas estuaries can be inferred by marsh vertical accretion rates and Holocene sediment thicknesses of these estuaries bayhead deltas. White et al. [2002] found that both vertical accretion rates and Holocene sediment thicknesses decrease from Galveston Bay southward to Matagorda Bay and Corpus Christi Bay. This trend indicates that suspended sediment loads transported via freshwater inflow from the rivers to these estuaries decreases from northeast to southwest. This trend follows a trend in decreasing precipitation from north to south. Thus, the climatic gradient controls fluvial sediment input into these estuaries. Nature has provided an opportune experimental design to study estuarine sedimentary processes and determine how the sediment dynamics of these systems are controlled by physical forcings and the influence of climate gradients.

1.3. Objectives

The objectives of this study are to use physical measurements collected by state and federal agencies to answer the following questions:

a. What is the dominant forcing(s) of suspended sediment concentrations in Texas estuaries?
b. Does the relative importance of fluvial, tidal, and meteorological forcing of suspended sediment vary among Texas estuaries?
c. Can suspended sediments variability among estuaries be explained by the climate gradient?

2. Physical Setting: Texas' climatological gradients

2.1. Precipitation / Inflow

In Texas, the major estuaries of Galveston, Matagorda, and Corpus Christi Bays lie along a precipitation gradient (Figure II-1) where average rainfall decreases from 117 cm/year in Galveston bay to 107 cm/year in Matagorda Bay and 72 cm/year in Corpus Christi Bay. This precipitation gradient results in a 10-fold decrease of average annual freshwater inflow (normalized by bay volume) from northeast to southwest as measured during the 2000 to 2010 time period. These inflow differences affect estuaries salinity regimes where Galveston Bay is a brackish system, Matagorda Bay oscillates between brackish to saline conditions, and the Corpus Christi Bay Estuarine system ranges from saline to hypersaline conditions due to the lack of inflow and high evaporation rates [*Montagna et al.*, 2012]

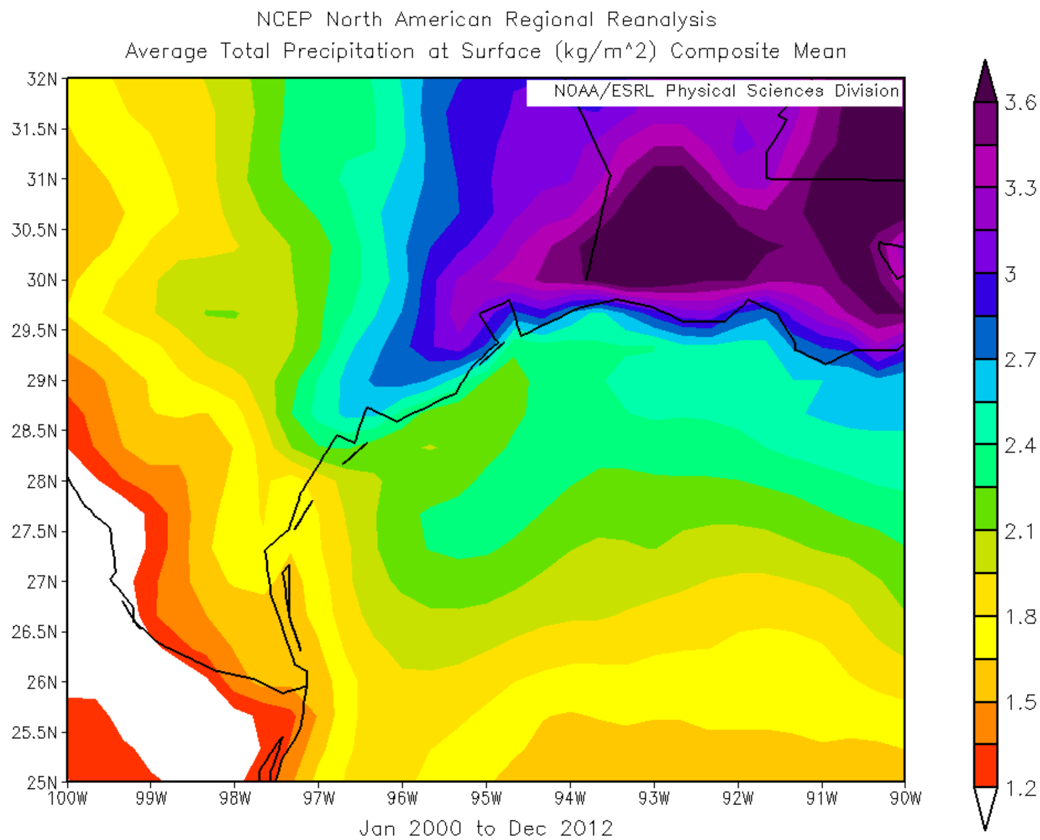

Figure II-1: Average total precipitation in kg*m^{-2} on the Texas coast. This precipitation gradient shows the climatological pattern during the period of this study.

2.2. Wind

An aeolian climate gradient also exists along the Texas coast including a gradient of wind speed with average annual wind speed increasing from 5.2 to 6.2 m/s from Galveston to Corpus Christi Bays (see Figure II-2). These estuaries are shallow, wind-dominated systems, prone to wave resuspension of sediment [*McKee and Baskaran*, 1999]. All bays share similar fetch lengths and average wave energy, derived from wind time series and a simple wave model, increasing two fold from north to south. Because fetch is similar in these estuaries, this wave-energy trend is caused by higher wind speed to the south.

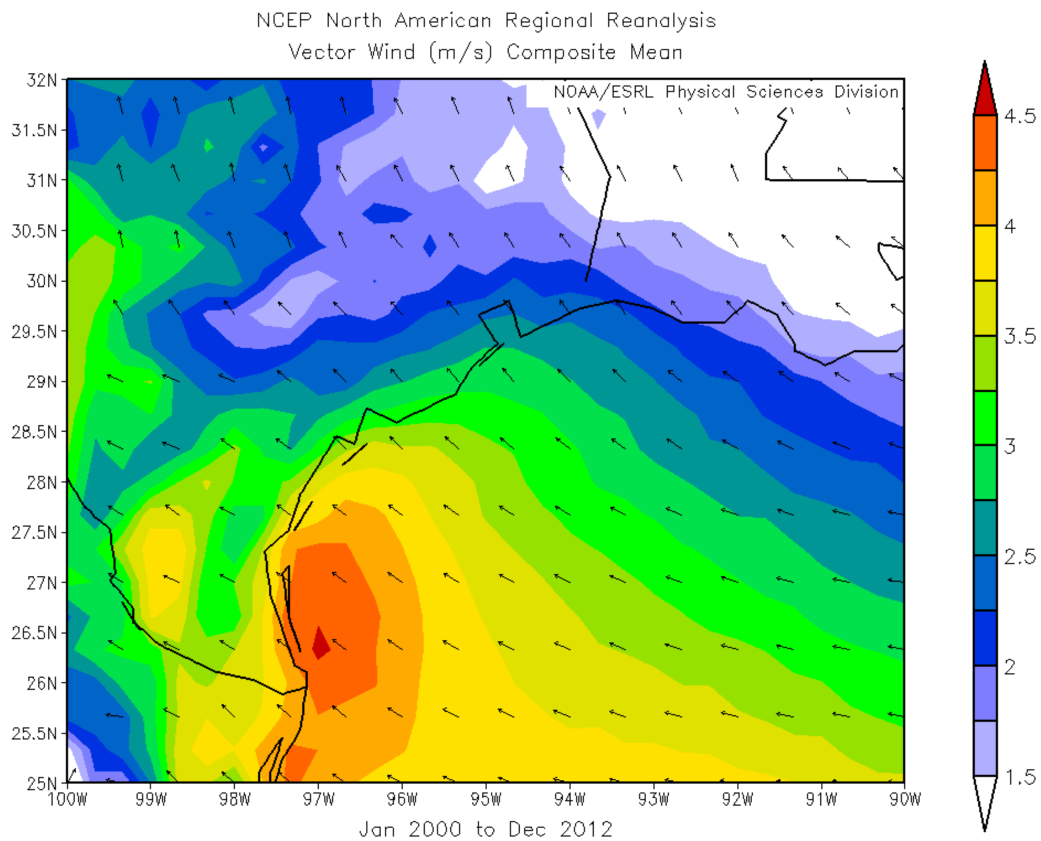

Figure II-2: Average wind speed and direction on the Texas coast illustrating the wind gradients climatologic pattern.

3. Study sites

3.1. Galveston Bay

The Galveston Bay estuarine system covers an area of 1416 km^2 and consists of East, Galveston, and Trinity Bays, and the Trinity and San Jacinto Rivers and other tributaries. The system connects to the GOM via the Bolivar Roads, and Rollover Pass tidal inlets (see Figure II-3).

Primary freshwater inflow into the system is from the Trinity River. The average depth is about 2.4 meters and average tide range is 34 cm (Table II-1). Median wind speed is 5.2 m/s from the southeast. During frontal passages, it has been observed that as much as half of the volume of Galveston bay can be evacuated. This is likely due to the geometry of the estuary and the position of Bolivar Roads with respect to the north winds [*Ward*, 1991]. While this bay's major river system is dammed, White et al. [2002] and Phillips and Slattery [2008] found that the creation of Lake Livingston had no effect on the transport of sediment to the Galveston Bay estuarine system.

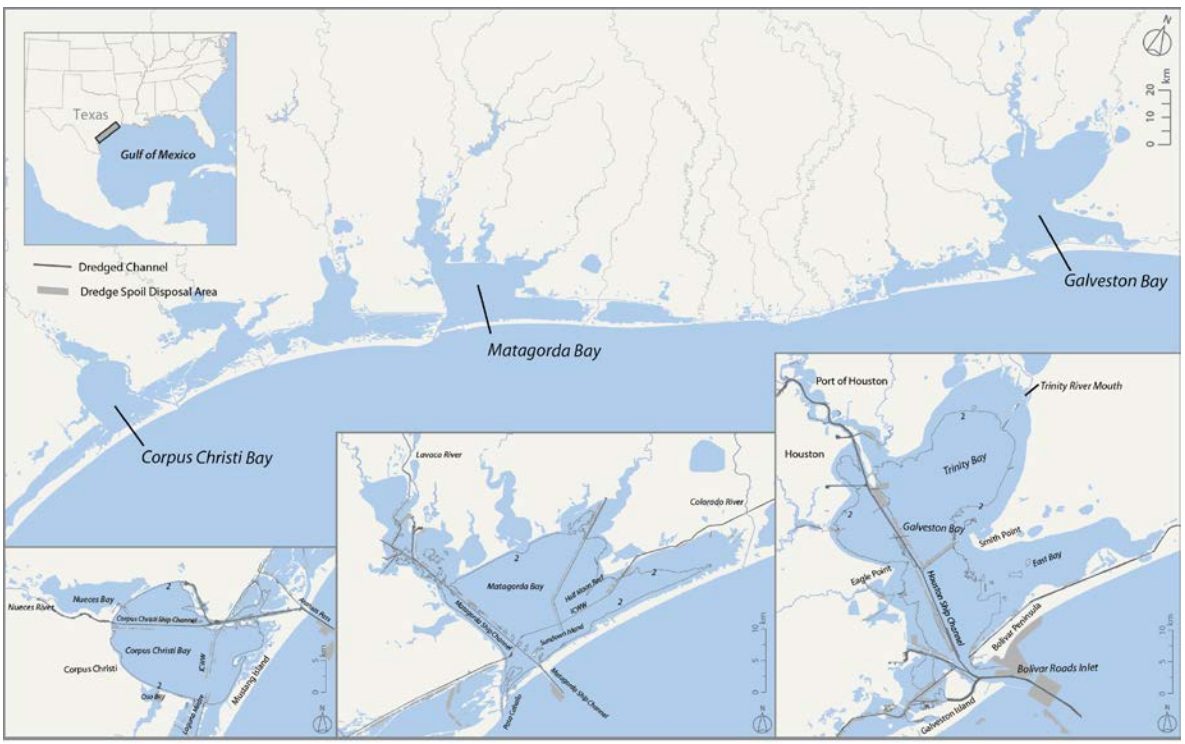

Figure II-3: Study sites along the Texas Coast with detailed maps of Corpus Christi, Matagorda, and Galveston Bays.

3.2. Matagorda Bay

Matagorda Bay estuarine system covers 1158 km^2 and includes the Colorado, Lavaca, and Navidad Rivers, Tres Palacios Creek and other tributaries, Lavaca and Matagorda Bay, and other secondary embayments see Figure II-3. The primary inflow into the system is from the Colorado River that flows into Matagorda Bay. Matagorda Bay is 3 meters deep on average with a tidal range of 17 cm (Table II-1). It is connected to the Gulf of Mexico by the two tidal inlets Matagorda Ship Channel and Paso Caballo. Median wind speeds are 5.7 m/s coming from the southeast (Table II-1).

3.3. Corpus Christi Bay

Corpus Christi Bay system covers 433 km^2 and is composed of a primary and two secondary bays: Corpus Christi, and Nueces and Oso Bays, respectively. Corpus Christi Bay is the smallest of the three bays in this study in terms of area yet it is the deepest bay on the Texas Coast averaging four meters in depth with an average tidal range of 30 cm [*Ward*, 1997]. It is connected to the GOM by two tidal inlets: Packery Channel and Aransas Pass. Median wind speed from the southeast is 6.2 m/s. The majority of freshwater inflow comes in through the Nueces River and flows into Nueces Bay [*Ockerman and Heitmuller*, 2010]. Shideler [1984] found that during times of high inflow of suspended sediments in Nueces Bay never entered into Corpus Christi Bay. However, when strong wind was blowing for a prolonged period from the north substantial amounts of sediment would be resuspended and spill into Corpus Christi Bay from Nueces Bay. He hypothesized that Nueces Bay is a fluvial sediment storage basin having a control valve that allows for release into Corpus Christi Bay that is activated by strong northerly wind during the frontal passage.

Table II-1: Physical measurements compared among Texas estuaries.
Listed from north to south: from the average depth, area, volume, (NOAA, 2001), average annual precipitation [1951-1980; Larkin and Bomar 1983], average annual freshwater inflow (1941-1999; Texas Water Development Board, http://www.twdb.state.tx.us/data/bays_estuaries/bays_estuary_toc.htm, median wind speed and direction TCOON (1999-2000) and tide range from TCOON, http://lighthouse.tamucc.edu/TCOON/HomePage

	Average Depth (m)	Area (km^2)	Volume (km^3)	Tide Range (m)	Rainfall (cm y^{-1})	Inflow (10^6 m^3 y^{-1})	Median Wind Speed (m/s)	Median Wind Direction (degrees)
Galveston Bay	2.4	1,416	0.088	0.32	112	14,000	5.2	141
Matagorda Bay	3.4	1,158	0.075	0.23	102	3,801	5.7	140
Corpus Christi Bay	4.0	433	0.049	0.17	76	298	6.2	135

4. Datasets

Time series of environmental data representing the major forcing identified by McKee and Baskaran [1999], wind, inflow, and tidal data, were collected for each estuary during the period of 2000 to 2010. This period was chosen because of the existence of continuous hourly wind records for all estuaries in the data collected by the Texas Coastal Ocean Observation Network (TCOON) and National Oceanic and Atmospheric Administration's (NOAA) National Water Level Observation Network (NWLON) see Figure II-4.

4.1. Suspended Sediment Data

The Texas Commission on Environmental Quality (TCEQ) Surface Water Quality Monitoring Information System (SWQMIS) collects surface water point measurements of suspended sediment. These point measurements were collected following the Total Suspended Solid (TSS) EPA STORET method 2450b, and are recorded in mg/l. Data were extracted from the SWQMIS [*Texas Commission on Environmental Quality*, 2008]. For this analysis, only suspended sediment data collected from the primary and secondary bays were used (Figure II-4).

TCEQ monitoring stations were removed from this dataset if they were near a jetty or a dike, located within a port or sheltered ship channel, or within rivers. TCEQ collects these suspended sediment data quarterly at dedicated sites; however the database also contains sporadic data that are collected for special projects in the estuarine systems. In this analysis TSS data is used as proxy for suspended sediments.

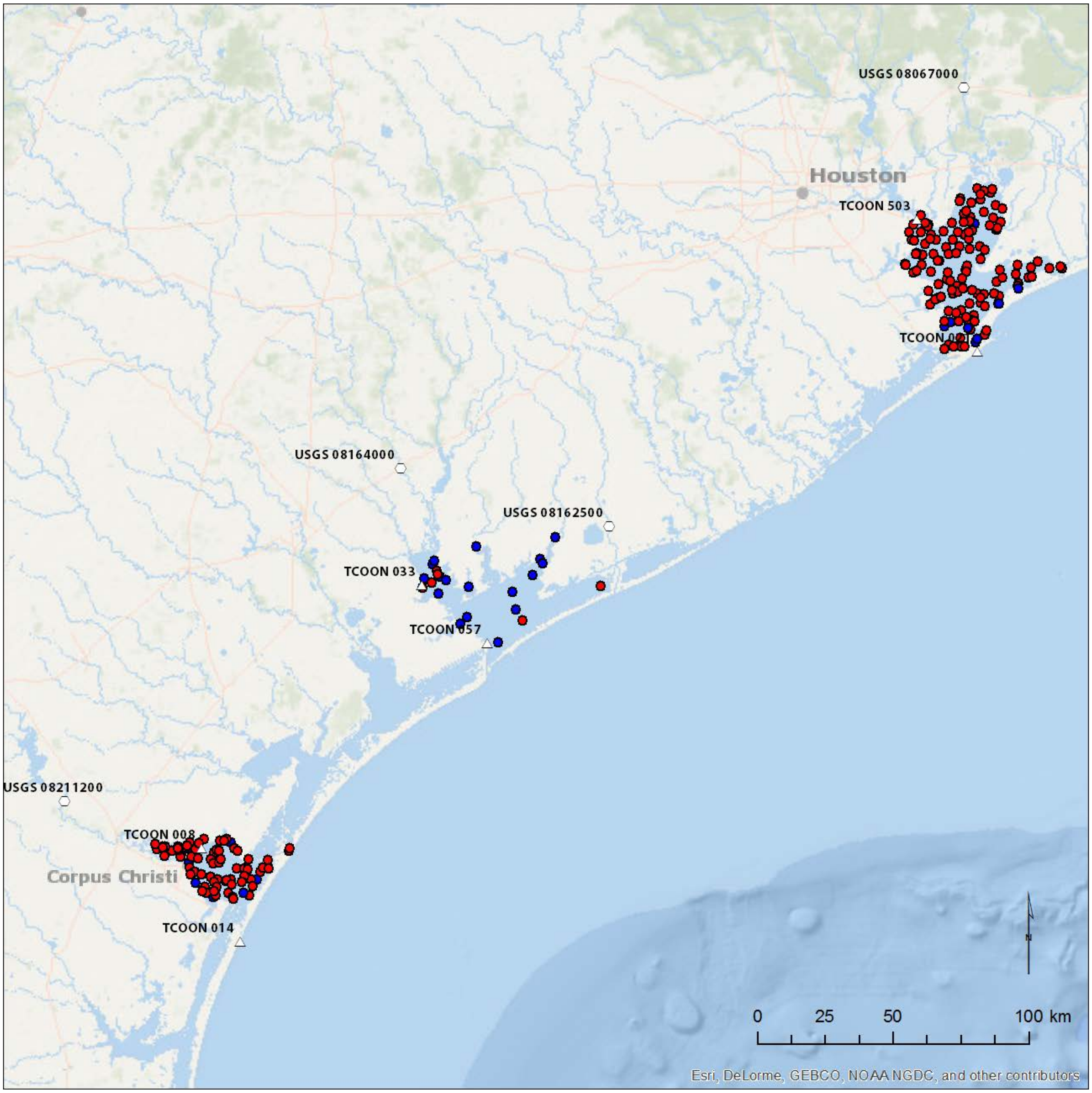

Figure II-4: Study Site with location of SWQMIS TCEQ, TCOON, and USGS stations.

4.2. Inflow data

The U.S. Geological Survey (USGS) collects daily stream gauge heights (Figure II-4) from the primary rivers entering the bays (Figure II-4). Gauge height (*GH*) data were used instead of discharge data because discharge data at these sites are more sporadic and contains large gaps in temporal data coverage. For Galveston Bay, data was collected from Trinity River at Livingston, TX, (USGS 08067000), for Matagorda Bay, Lavaca Rive near Edna, TX (USGS 08164000), and for Corpus Christi Bay, Nueces River at Bluntzer, TX (USGS 08211200). USGS station gauge height data gaps were filled using a spline to interpolate missing values if the gaps were less than three days. Gaps greater than three days were omitted from this analysis.

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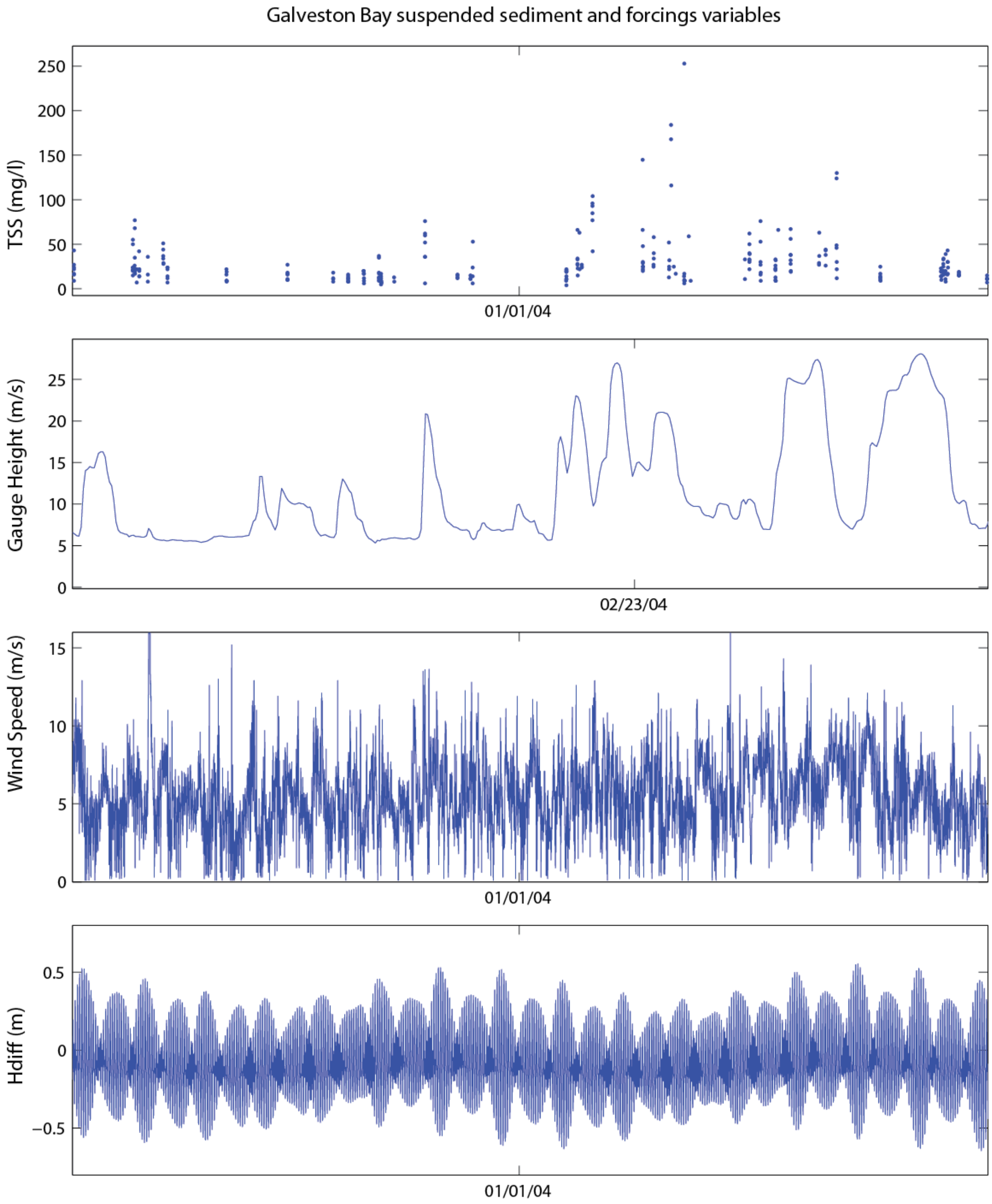

Figure II-5: Example of forcing datasets for Galveston Bay used in this study.

4.3. Wind and tide data

Hourly wind speed (*WS*) and direction data were collected for each estuary for the 2000 to 2010 period. All bays have TCOON and National Water Level Observation Network (NWLON) platforms that monitor wind speed within or near each estuary. Gaps in these data were substituted with National Oceanic and Atmospheric Administration's (NOAA) North American Regional Reanalysis (NARR) surface wind for the grid location including the platform [citation]. For Galveston Bay, wind data were collected at Galveston Pleasure Pier (NWLON Station 8771510), for Matagorda Bay wind data were collected at Port O'Connor (TCOON Station 057), and for Corpus Christi Bay the Bob Hall Pier (NWLON Station 8775870). *WS* data were then squared to NOAA hourly tidal predictions were downloaded for each estuary. The differences in tidal predictions between a GOM station and a station within the estuary were computed for each bay as a proxy for tidally generated currents. The water level differences indicate the slope of water surface forced by tidal forces only with higher differences indicating stronger currents. The stations of Pleasure Pier and Morgan's Point were used for Galveston Bay, Bob Hall Pier and Port Lavaca for Matagorda Bay, and Bob Hall Pier and the Lexington for Corpus Christi Bay. Tidal prediction differences *(Hdiff)* rather than water level differences were selected to focus on the impact of tidally driven currents without the influence of wind forcing.

5. Methods

5.1. Compilation of datasets.

All TSS data and forcing time series were placed into Matlab 2014a for computations and statistical analyzes. TSS measurements were synchronized with forcing variable's time series for their respective estuaries. Forcing variable data (wind and tides) was then extracted for periods of 36 hours and 6 days prior to TSS measurements. This was done to explore time lags in the relationships of TSS data with forcing data. The wind data were further modified to reflect that wave climate builds over time. This is reflected in the computation below by summing wind speed squares over a defined number of past hourly measurements. The wind speed was squared to better represent the shear force imparted by the wind to the water surface. The length of the wind speed squared time series was selected as 36 hours as the maximum correlation coefficients were all obtained for a lag within the first 36 hours (see Figure II-5).

$$SWS^2n = \sum_{n=0}^{lag\ max} WS_n^2 \text{ (Equation 1)}$$

Where WS is the wind speed at lag n equal to cumulative sum of the wind speed squared at lag n represented as SWS^2.

5.2. Statistical Analysis

To identify the dominant forcings of suspended sediments in these estuaries and their relative contributions two analysis methods were employed, a correlation analysis [*Wilks*, 2011] and a machine learning approach using backwards variable elimination with neural networks [*Olden et al.*, 2004]. For the correlation analysis a non-parametric measure were used , Spearman-rank correlation between respective forcings and measured TSS to determine dependence of TSS with the forcing. Spearman-rank correlation method was chosen because the method reduces the influence of outliers and because the response of suspended sediments to forcing parameters, maybe a nonlinear process.

5.3. Correlation Analysis

Spearman-rank correlation coefficients (r_s) were generated for each TCEQ station if the total number of measurements for the period of study was greater than 20 to ensure significant relationships. We further calculated r_s between the time-lagged forcing variables and the single TSS measurements collected by TCEQ similar to the method of Shideler [1984] at each time step. This was done to investigate if prior conditions of environmental forcings may have influenced the measured concentrations of TSS. This is in recognition that environmental conditions present when suspended sediment samples were taken may not have contributed to their presence. For wind and tidal data correlations, lags were computed hourly and for inflow data, lags were computed daily. Correlation lags for wind and tidal data were computed for 36 hours and inflow data for 12 days.

5.4. Statistical learning approach

In recent years machine learning techniques have increased in the popularity of use for studying natural systems [*Haupt et al.*, 2008; *Hsieh*, 2009]. These techniques capitalize on the increases in computing power and advances in statistical methods for analyzing large datasets [*May et al.*, 2011]. Machine learning techniques are able to learn nonlinear patterns in data and create better predictive models using algorithms that were once unable to be implemented due to processing time and data storage limitations. One of the most popular of these techniques is Neural Networks (NNs). Originally NNs were inspired by neurons in the human brain. Over the past twenty years they have been used for a variety of applications in many fields including coastal sciences. Examples include water level predictions [*Nam et al.*, 2002], sediment resuspension [*van Maanen et al.*, 2010] and a variety of others.

Each estuary was studied to determine dominant forcing(s) of suspended sediments. To do this we employed backwards elimination variable selection was employed using a neural network as a function representation of forcing influence on TSS outcome [*Olden et al.*, 2004]. This approach (detailed below) builds predictive models from the forcing variables to estimate TSS using neural networks. It first optimizes for model structure based on minimum mean square error (MSE) then applies backwards selection to assess variable influence. A Neural Network approach was chosen for this task because it is able to capture nonlinear relationships, such as those between sediment resuspension and its forcings. In a Neural Network there are no formal assumptions of the relationship between predictors and predictand, and they are effective at learning complex relationships with large datasets, [*Olden et al.*, 2004; *Hsieh*, 2009; *May et al.*, 2011]. Neural networks are increasingly being used to predict suspended sediment concentration in fluvial and marine environments and are able to account for the nonlinearity of a system [*van Maanen et al.*, 2010].

First, a full model was created, for each estuary, by including as input into the neural network all physical forcing variables that have a potential to modify TSS concentrations. These forcing variables were selected based on an initial correlation analysis of wind-wave resuspension, tidal current, and inflow proxies. For SWS^2, *Hdiff* , and *GH*, the time-lagged variable with the highest correlation r_s for each station were used as inputs. Also included were TCEQ station latitude and longitude and mean fetch length for the time period associated with the time-lagged. These location and fetch variables were added to include spatial variability within the water bodies. While one value each of SWS^2, astronomical tidal current, and inflow values is considered for each bay and time step, TSS sampling can be conducted at multiple sites on the same day, within hours of each other. There are only single inputs for forcing variables and multiple TSS samples taken on one day, that may not covary in space most of which is being accounted for by including location data and fetch length. All input forcing variables were z-scored and TSS data were scaled from 0 to 1 using minimum and maximum values following the methods of Olden [2004].

A single hidden layer NN with tansig input and purelin output. The neural network architecture (i.e. number of hidden neurons) for the full model was optimized based on MSE as an indicator of predictive performance using the testing set data [*May et al.*, 2011]. The number of hidden neuron in each model were sequentially increased in each model run and ran 100 ensemble members for each increase in the number of hidden neurons. Each model run was run with randomized training using 60% of the data and testing data representing 15% and 15% of the data used for validation, respectively. Using the 100 runs for a given architecture, we calculated mean MSE and standard error. The best model architecture was then chosen as the one with the minimum MSE for each estuary. If MSE among models did not differ significantly (α=0.05), the model with the smallest architecture was chosen for backwards elimination to determine variable importance.

Once the full models were optimized were then implemented the neural networks a variable importance approach using a backwards elimination method as outlined in [*Olden et al.*, 2004]. To assess influence, an input variable was set to random noise while the others were preserved. This effectively eliminates the variable while retaining the model structure (Table II-2). Ranking of a variable's importance was then calculated based on the percentage reduction in MSE compared to the full and removed-variable model based on the training set and this process was repeated 100 times with randomized training and testing data to determine if models mean MSE did not differ significantly (α=0.05), from each other.

Table II-2: Combination of input variables considered in NN models

Model	**Inputs**
Full model	*SWS*^{2}, Mean Fetch, Gauge Height, Harmonic Water Difference, Latitude, Longitude
Model WOwind	Gauge Height, Harmonic Water Level Difference, Latitude, Longitude
Model WOinflow	*SWS*^{2}, Mean Fetch, Harmonic Water Level Difference, Latitude, Longitude
Model WOtide	*SWS*^{2}, Mean Fetch, Gauge Height, Latitude, Longitude

6. Results

6.1. Correlation analysis

Results for the correlation analyses are presented in Figure II-6. Each of the nine boxplots illustrate the distribution of correlation coefficients computed for each station between forcing variables and TSS with increasing lags. Values are computed for lags up to 36 hours for wind and tidal forcings and for up to 12 days for inflows. The plots are presented for each bay (columns) and each forcing variable (rows). The median r_s are highest for wind forcing for all bays with maximum values of 0.38, 0.58 and 0.54, respectively for Galveston, Matagorda and Corpus Christi Bays. The values are obtained for lags of 26 hours, 14 hours and 34 hours for the three bays.

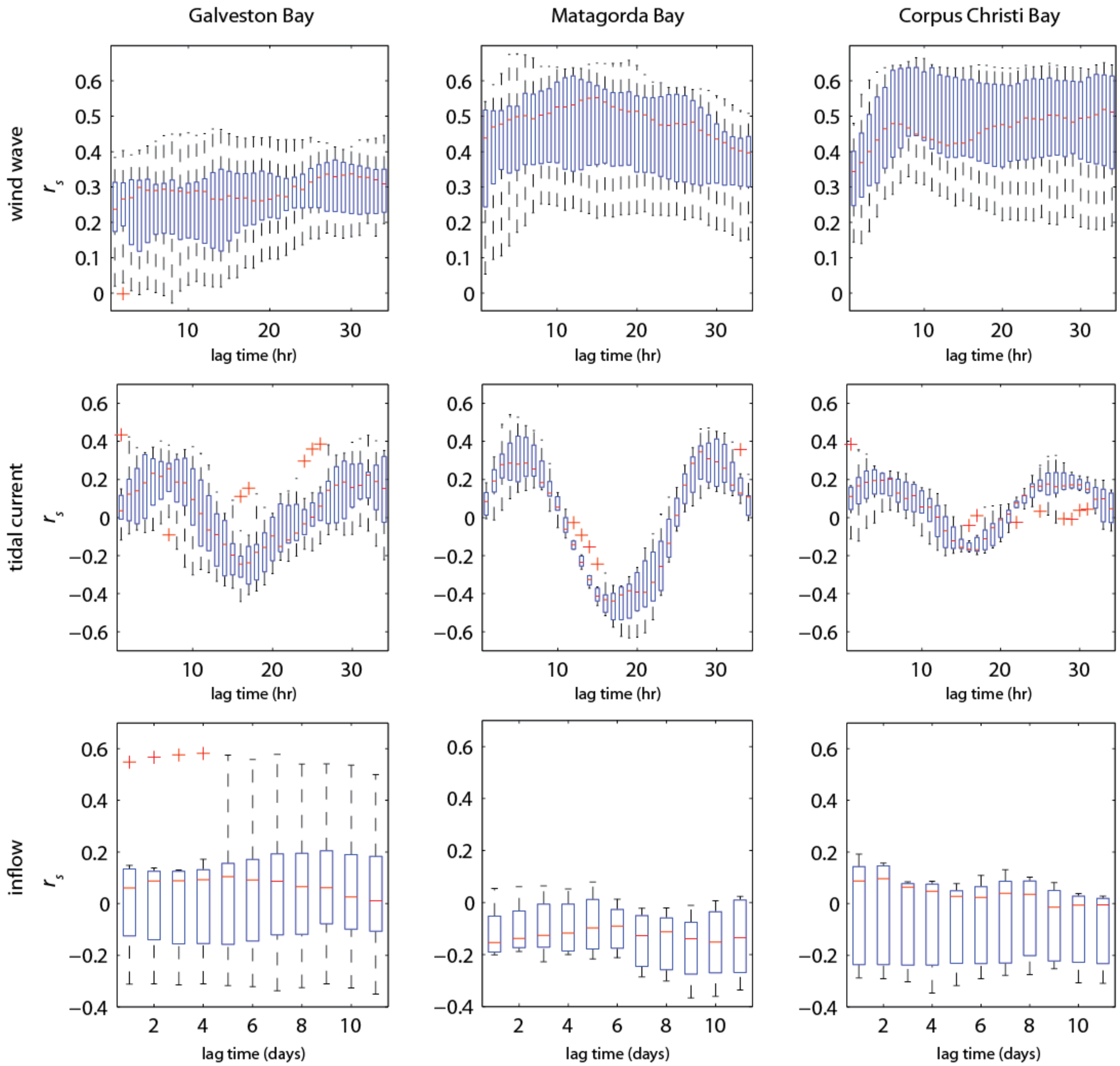

Figure II-6: Results from the correlation analysis. The plots for each bay (columns) and each forcing variable (rows). The y-axes represent spearman rank correlation with TSS and the respective forcing. The x-axes represent time since measurement was taken. Each plot represents results for all stations with greater than 20 samples (Figure III-3).

The middle row presents the results for the correlation with tidal current proxies *Hdiff*. The results include the expected 12 hour tidal periodicity. The median correlation coefficients have maximum values of 0.38, 0.46 and 0.23, respectively for Galveston, Matagorda and Corpus Christi Bays. The values are obtained for lags of 6 hours, 5 hours and 7 hours for the three bays.

The correlation coefficients are, however, not statistically significant except around the areas of maximum and minimum correlations with the tidal signal.

The last row displays results from the correlation analyses with riverine inflows. The results are significantly different for Galveston Bay as compared to Corpus Christi and Matagorda Bay. For the latter two estuaries, the correlations are not statistically significant. For Galveston Bay, while the correlation coefficients are not significant with inflow for most locations within the bay, Figure II-6 identifies several outliers with correlation coefficients up to 0.58. The high correlation values are for station locations nearest to the mouth of the Trinity River.

6.2. Neural Network Modeling Variable Importance

The neural network architecture chosen from MSE optimization included seven hidden neurons for Galveston Bay and one hidden neuron for both Matagorda Bay and Corpus Christi Bay for the models including all forcings. The corresponding MSEs for the three models are presented in Table II-3. The full model for Matagorda Bay, MSE =7.59E-03 , outperformed both the Corpus Christi, MSE = 3.53E-03, and Galveston Bay full models MSE =5.87E-03. The models were then updated following the backward elimination progression to identify the respective importance of forcing variables. Removing the wind-wave forcing variables showed the highest reduction in model performance for all estuaries. The other significant decreases in model performance, although of lesser relative importance, were observed for the inflow forcing variable in Galveston Bay and the tidal currents in Matagorda Bay. The results are summarized in Table II-4. Corpus Christi did not show any significant decreases in model performance from variable removal.

Table II-3: Test performance (MSE) of models runs used in variable importance determination

	full	std error	WOtide	std error	WOriver	std error	WOwind	std error
Galveston Bay	5.87E-03	1.24E-04	5.81E-03	1.21E-04	6.24E-03	1.38E-04	6.79E-03	1.46E-04
Matagorda Bay	7.59E-03	3.04E-04	8.51E-03	3.57E-04	8.33E-03	3.37E-04	1.04E-02	4.94E-04
Corpus Christi Bay	3.53E-03	3.22E-04	3.53E-03	3.17E-04	3.95E-03	3.56E-04	4.76E-03	4.06E-04

Table II-4: Forcing variable importance represented by testing set percent change of performance determine by NN models. Bold indicates removal of forcing variable leads to statistically significant difference when removed from the full model

	tidal currents	inflow	wind-wave resuspension
Galveston Bay	0.95%	**-6.36%**	**-15.67%**
Matagorda Bay	**-12.15%**	-9.74%	**-37.31%**
Corpus Christi Bay	-0.03%	-12.00%	**-34.95%**

7. Discussion

The aforementioned analyses establish that wind is the most dominant forcing controlling spatial and temporal variability of suspended sediments in Galveston, Matagorda and Corpus Christi Bays. Wind forcings influence is less in Galveston Bay, most likely due to the wind climate gradient (Figure II-2). Galveston Bay is influenced by lower wind speed as compared to the other bays studied. Also the depth of Galveston limits its ability to generate wave energy under the same wind conditions as in the other bays. Another factor which could also account for lower correlations in this bay is the high amount of inflow. On non-windy days high input of suspended sediments could contribute to reducing the correlation with wind forcing variables as inflow into Galveston Bay in more frequent than in other bays.

For Matagorda Bay, wind forcing was the most important variable compared to other estuaries, and it had higher median correlations with wind than the others. This indicates that wind wave resuspension is more influential in Matagorda Bay than the other bays. However, the results for Matagorda Bay could be influenced by the location of the stations. The majority of the TCEQ stations in this estuary are located in Lavaca Bay which has the longest fetch length directly aligned with the predominant southeasterly wind direction see Figure II-3. Matagorda Bays tidal currents seem to effect variability of suspended sediments in the bay. Matagorda has the deepest inlet, Matagorda Channel, on the Texas Coast. The tidal flux in Matagorda Bay may be greater than that of Galveston and Corpus Christi Bays accounting for the greater influence of tides on the transport and variability of suspended sediments there.

Corpus Christi Bay is solely dominated by wind forcing. No significant results were found with inflow comparisons here. The influence of inflow in this bay is likely very low. The sampling methodology that TCEQ employs, however, can completely miss pulsed events into these estuarine systems. It is hard to determine inflow influence on suspended sediment in this bay without higher density of sampling in both space and time. Tides seem to minimally influence the variability of suspended sediments in this bay. This most likely is due to the bay having smaller cross sectional width at the inlet, which makes its tidal exchanges more restricted than those of Galveston and Matagorda Bays.

Corpus Christi Bay seems to be solely dominated by wind forcing correlations with wind. No significant results were found with inflow comparisons here. The influence of inflow in this bay is likely very low. This may be the case, however, the sampling methodology that TCEQ employs can completely miss pulsed events into these estuarine systems. It is hard to determine inflow influence on suspended sediment in this bay without higher density of sampling in both space and time. Tides seem to minimally influence the variability of suspended sediments in this bay. This most likely is due to the bay having smaller cross sectional width at the inlet, which makes it tidal exchanges more restricted than those of Galveston and Matagorda bays.

Improvements to this analysis could come from higher density sampling in time and space. The methodology suffers from the locations of long-term sampling stations in the estuaries. TCEQ SWQMIS monitors ports and navigation areas rather than unmodified areas such as open bays. The quarterly sampling method removes the influence that extreme events have on the overall variability of the estuarine systems (State sampling is conducted only when conditions are safe). Future analysis should employ satellite remote sensing of TSS. This will increase both spatial and temporal sampling of suspended sediments in these estuaries and provide better insight to the understanding of the physical influence these forcing have on the variability of suspended sediments.

8. Conclusions

This study shows that wind-wave resuspension is the dominant forcing controlling estuarine suspended sediments in Galveston, Matagorda, and Corpus Christi Bays. Freshwater inflow is an important forcing for the entirety of Galveston Bay even overcoming wind-wave resuspension forcing for locations nearest to the mouth of the Trinity River. The stronger influence of riverine inflow in Galveston Bay is linked to the precipitation gradient along the Texas coast. Tidal currents were found to be important in Matagorda Bay but less significant for Corpus Christi and Galveston Bay. Tidal currents are most likely important for the transport of suspended sediments once in suspension rather than directly generating resuspension and their higher importance in Matagorda Bay is likely in part due to the location of the study station.

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CHAPTER III: ESTIMATION OF TOTAL SUSPENDED SOLID IN TEXAS ESTUARIES: A MODIS REFLECTANCE RATIO ALGORITHM.

1. Introduction

Understanding the dynamics of estuarine sediments is necessary from managerial, ecological, and geological perspectives. Suspended sediments are indicators of water quality and ecosystem health and are a critical input to the morphodynamics of the estuarine system [*Ward and Montague*, 1996; *Green and Coco*, 2014]. Studying suspended sediments within estuaries can be arduous and time-consuming. Often a few point measurements within an estuarine system are used to characterize the overall condition of the system [*Ward and Montague,* 1996]. These measurements are not only costly, but also are biased by sampling logistics. Boats are mostly deployed when weather conditions are fair; thus samples are biased to fair-weather conditions [*Ward and Montague,* 1996]. While these measurements provide much-needed data, their lack of spatial and temporal coverage creates impediments when trying to characterize the complexity and heterogeneity of an estuarine system. Estuaries are highly dynamic environments and the conditions observed at a single point can be the result of many complex and interrelated processes [*Ward and Montague*, 1996]. Thus, the observations may not reflect the system in space or throughout time.

To bridge the spatial gap caused by traditional sampling, Shideler [1984] employed a US Coast Guard helicopter rather than a boat to sample Corpus Christi Bay, Texas. Shideler was able to sample 14 points throughout the estuary within 5 hours and produced some of the first quasi-synoptic measurements of suspended sediments in this region. He repeated this sampling methodology a total of eight times and was able to characterize the dominant spatial patterns of suspended sediment distributions and characterize the bays response to wind-wave resuspension from prevalent frontal passages and predominant southeasterlies. Further advances in the monitoring of suspended sediments came when Stumpf and Pennock [1989] discovered that weather satellites were able to quantify suspended sediments. This work ushered in the usage of satellite remote sensing in the monitoring of suspended sediments and provided synoptic views of suspended sediment dynamics. The usage of these satellites allowed for the creation of some of the first Environmental Data Records EDRs (EDR) of suspended sediments acquired daily and spanning decades [*Stumpf and Pennock*, 1989; *Ruhl et al.*, 2001].

In recent years, satellites have been used to monitor suspended sediment and other water quality parameters such as chlorophyll-a (CHL-a) and colored dissolved organic matter (CDOM) [*Matthews*, 2011]. Most of the research has focused on oceanic areas[*McClain*, 2009]. There is now, however, much interest to study estuaries and coastal areas using satellites [*Miller and McKee*, 2004; *D'sa and Miller*, 2005; *Zawada et al.*, 2007; *Doxaran et al.*, 2009; *Chen et al.*, 2010; *Petus et al.*, 2010; *Feng et al.*, 2014]. Depending on a satellite's orbit, spectral resolution, and spatial resolution, coastal regions can be covered daily, providing a better understanding of the dynamics and variability of their waters. Overflights from polar-orbiting satellites carrying National Aeronautics and Space Administration's (NASA)'s Moderate-Resolution Imaging Spectroradiometer (MODIS) provide two almost-daily images of estuaries and coastal areas. The MODIS sensor onboard NASA's Aqua satellite has been in orbit since 2002. MODIS was designed with 36 spectral channels to support observations of oceans, land, and clouds [*McClain*, 2009]. There are nine, 1-km bands that were designed for ocean color observations in the visible to near-infrared (NIR) (412-816 nm) portion of the electromagnetic spectrum. Over turbid waters of inland and coastal areas, however, the dynamic range of the sensor can be exceeded, leaving the actual signal to be unknown [*Franz et al.*, 2006]. Many researchers are now using the land/cloud bands to quantify suspended sediment concentrations in coastal waters [*Matthews*, 2011]. These land/cloud bands are less sensitive than the 1-km ocean color bands, have broader dynamic ranges and do not suffer from the problems of the higher resolution ocean color bands [Franz et al., 2006]. The land (1,2) and cloud bands (3-9) have spatial resolutions of 250 and 500 meters, respectively. Band 1 is optimal for detecting suspended sediment due to high reflectance from sediment in the water column around the red portion of the spectrum centered at 645 nm. Using the red portion of the spectrum, quantifying suspended sediments has little impact from phytoplankton pigments, such as CHL-a, in low concentrations [*Bukata*, 1995]. Yet, in high concentrations of phytoplankton (CHL-a > 30mg/l), the red portion of the signal can be influenced and the strength of reflectance of suspended sediments reduced [*Ritchie and Zimba*, 2006]. The combination of high spatial resolution, daily-repeat time, and a greater than 12-year data period, makes MODIS-Aqua data ideal for creating an EDR of suspended sediments.

The objective of this study was to develop an inversion algorithm to create an EDR of suspended sediment in Texas estuaries using MODIS satellite reflectance data. The combination of a long-term water quality monitoring dataset with the long-term data record (LTDR) of the MODIS dataset is optimum for filling spatial and temporal gaps that in situ measurements acquired by state agencies and other researchers lack. To the knowledge of the authors, no published studies have quantified total suspended solids TSS from satellites in the estuaries of Texas. This method takes advantage of the Texas Commission on Environmental Quality TCEQs long-term in situ data and combines it with NASAs MODIS to quantify total suspended solids (TSS) concentrations allowing for the development of a LTDR in Texas estuaries.

2. Study Area

This study was conducted along the Texas coast within the estuarine systems. To gather a large amount of data from the TCEQ database we included all the bays and estuaries between Galveston and Corpus Christi Bays including Matagorda Bay, Aransas Bay, and San Antonio Bay (Figure III-1).These shallow-water estuaries are drowned river valleys that formed during the Holocene after the last sea-level low stand. They are separated from the Gulf of Mexico by a thin chain of barrier islands and spits that span the length of the Texas Coast [*Davis and FitzGerald*, 2004; *Davis*, 2011]. All of these estuaries are shallow-water microtidal wind-dominated systems, and most of them have inlets that connect them to the Gulf of Mexico[*McKee and Baskaran*, 1999]. The main source of estuarine bottom sediments is thought to be freshwater inflows, that have been infilling the estuaries for thousands of years [*Shepard*, 1953; *Nichols*, 1989; *Yeager et al.*, 2006]. Thus, the bottom sediments and those in suspension mostly consist of fine-grained silt and clay [*McKee and Baskaran*, 1999].

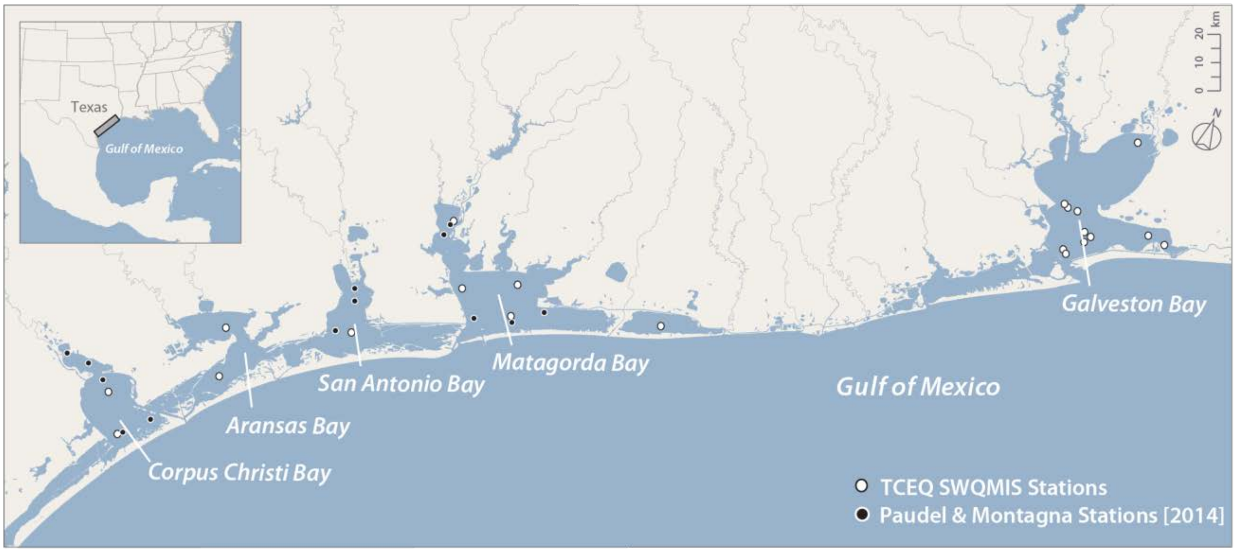

Figure III-1: Texas estuaries and in-situ data collection sites of the Surface Water Quality Monitoring Information System (SWQMIS) and Paudel and Montagna [2014]

3. Datasets

3.1. In-situ data

The in situ suspended sediment data used in this analysis was collected by the Texas Commission on Environmental Quality (TCEQ). The TCEQ catalogs its surface water samples in the Surface Water Quality Monitoring Information System (SWQMIS) [*Texas Commission on Environmental Quality*, 2008]. TCEQ in situ measurements are collected following the Total Suspended Solid (TSS) EPA STORET Standard Method 2450b. This measurement involves taking a volume of water from a point within an estuary and passing through a pre-weighed glass fiber filter. The filter is then dried and weighed with the mass of the sample divided by the volume of water filtered, normally, denoted in mg/l. These measurements are typically made quarterly, however, some sites in the dataset are sampled sporadically for special projects. Data were extracted from the SWQMIS [*Texas Commission on Environmental Quality*, 2008] for the period spanning 2002-2010. For this analysis, only TSS data collected from the primary and secondary bays (Figure III-1) were used. If coincident sampling of chlorophyll-a (CHLA) was present, this too was extracted. TCEQ station data was omitted to avoid mixed land-water pixels in the reflectance data if stations were within a kilometer of the shoreline. Measurements were also removed if they were located within or near Sabine Lake and any points south of Corpus Christi Bay. Sabine Lake data were removed because the CDOM-rich water coming from the Neches River may bias the optical signal. Areas south of Corpus Christi Bay were left out of the input dataset because bathymetries the area is relatively shallow, and the possibility for bottom reflectance contaminating the single is high. As a result a total of 704 in-situ samples was left for inputs for model development.

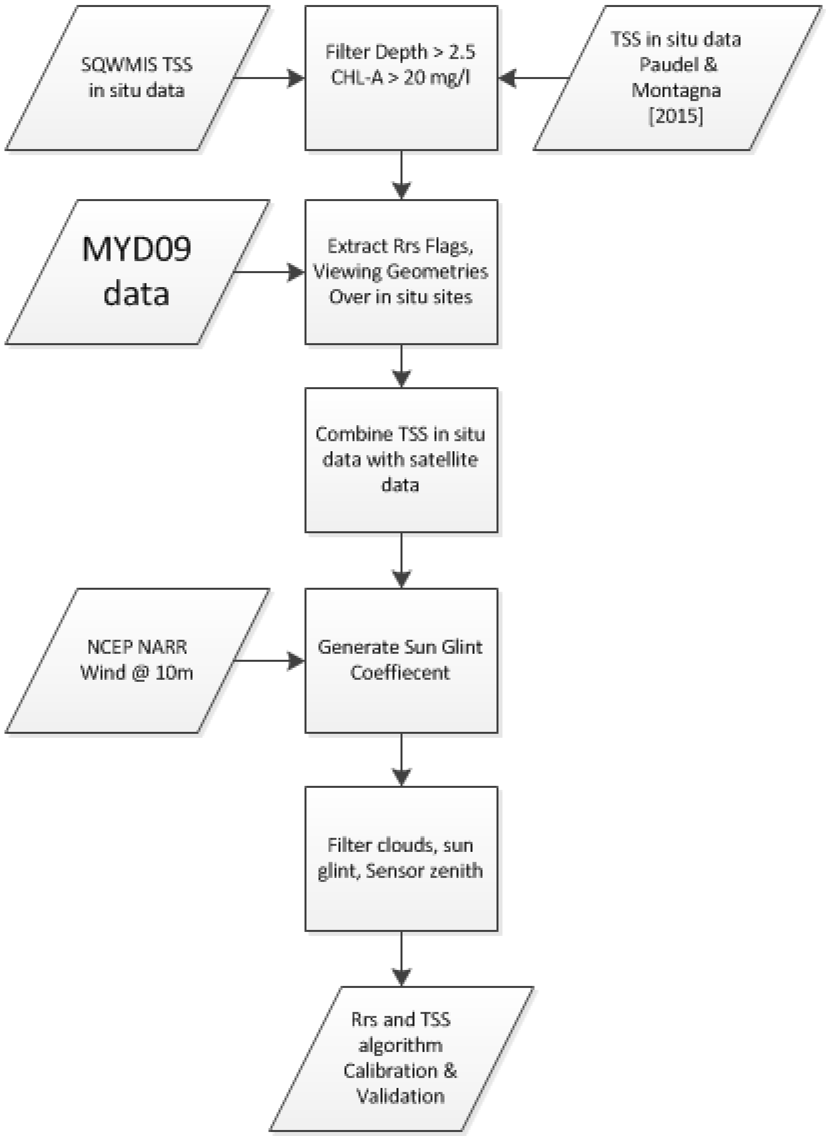

Figure III-2: Flow chart detailing the processing of input data into the final data used for model calibration and validation.

3.2. Satellite data

Recently, MODIS land data products have been used to quantify suspended sediments in coastal estuaries with 250-m and 500-m MODIS data [*Doxaran et al.*, 2009; *Feng et al.*, 2014]. Doxaran et al. [2009] used the MYD09 and its counterpart MOD09 to quantify suspended sediments accurately in the Gironde estuary, France. The MODIS Surface-Reflectance Products (MOD09 and MYD09) are generated from MODIS Level 1B for land bands 1, 2, 3, 4, 5, 6, and 7 and are estimates of surface spectral reflectance corrected for both atmospheric scattering and absorption [*Vermote and Kotchenova*, 2008]. Doxaran et al.[2009] developed an algorithm using a remote sensing reflectance (*Rrs*) ratio of Bands 1 and 2, red and near-infrared, respectively. In their study, they found that the atmospheric correction used by the land data community was sufficient to quantify suspended sediments ranging from 77 to 2182 g/m^3. This study took a similar approach because little effort was needed to acquire accurate *Rrs* data over Texas estuaries. In this study, only the MYD09GA dataset was chosen for use rather than using both like Doxaran et al. [2009]. During the morning observation time of the MOD09 dataset, large amounts of clouds usually occlude the estuaries but normally dissipate prior to the MYD09 19:30 UTC observation time, however, clouds may persist during this time as well. This study also differs from Doxaran et al. [2009], because it expands the spectral data to the blue and green, 500-meter bands by using the MYD09GA product. While this product has a lower spatial resolution, including it provides more spectral information for algorithm development, and it also includes a cloud detection flag. As for the 500-m spatial resolution, we found that it was sufficient to show the major responses of suspended sediments to their respective forcings in these estuaries.

3.3. Sun Glint Calculation

Over water, significant areas of remotely-sensed satellite imagery can be contaminated with sun glint, a disk-like spot that has higher reflectance values than the surrounding area in the satellite imagery. Frensal reflection causes sun glint and its magnitude is dependent on a combination of complex interactions of surface roughness of the water, that is influenced by wind speed and direction, and solar and sensor viewing geometries [*Zhang and Wang*, 2010]. MODIS data is routinely contaminated by sun glint because the satellite does not have a glint tilting avoidance strategy [*Wang and Bailey*, 2001]. The MYD09GA data product does not include a glint coefficient like SeaDAS outputs because its use is for land applications; thus, *Rrs* data over water is sometimes contaminated by sun glint. We, therefore, implemented the sun glint algorithm created by Bailey and Wang [2001]. Use of this algorithm allowed for the removal of contaminated *Rrs* data from inputs into algorithm development and the removal of contaminated data in the TSS EDR created from this study. Wind speed data was extracted from the National Center for Environmental Prediction's (NCEP) North American Regional Reanalysis model (NARR) [*Mesinger et al.*, 2006] for the locations and time of the MODIS image capture for input into the sun glint algorithm.

3.4. Validation Data

An independent dataset collected by Paudel and Montagna [2014] was used to validate the final TSS algorithm. These data were collected in Matagorda, San Antonio, and Corpus Christi Bays, and follow the same methods as the TCEQ SWQMIS. Sampling sites are spread over these estuaries and provide quarterly sampling from 2011 to 2013. In total, there were 135 cloud free data points that were available. Surface water samples for TSS and CHL-a were collected for every in-situ location. Usage of this independent dataset gave an impartial assessment of the final algorithm's accuracy and illustrated its robustness.

4. Methods

The MYD09GA data products were downloaded using NASA's Reverb data discovery tool (http://reverb.echo.nasa.gov/) for each day that data was available in the SQWMIS database.

From the 709 in-situ samples, a total of 294 unique days of satellite data were available. Satellite data collected from Reverb spanned from 8-13-2002 thru 5-3-2010. NASA's SeaDAS 7.0.1 software was then used to extract *Rrs* data, viewing geometries, and flags from MYD09GA files over the SWQMIS collection sites when concurrent collections were within four hours of the overflight of the satellite. After data extraction was complete, MYD09GA data were combined with SQWMIS in situ data. To avoid the influence of bottom reflectance and algal absorption on *Rrs* data, it was removed if 1) it was collected at depths less than two meters unless TSS values were greater than 50 mg/l, and 2) it had CHL-a values greater than 30 mg/l following suggestions from [Bukata, 1996], which is similar to the approach of Stumpf and Pennock 1989]. Sun glint coefficients were generated following Bailey and Wang [2001]. Data were also removed, if 1) it was flagged as cloud reflectance in the MYD09 dataset, 2) sun glint coefficient was greater than 0.001 [*Bailey and Wang*; 2001], and 3) sensor zenith angles were greater than or equal to 60 degrees (Figure III-2). After these data had been filtered, 54 of the 703 data points remained for the development of the TSS model with TSS values ranging from 4 to 178 mg/l.

Next, Spearman Rank correlation coefficients were generated from *Rrs* Bands 1-4 and combinations of *Rrs* ratios between TSS to determine the best candidates for inputs into the model. Spearman correlation was used because it is less influenced by outliers and can show nonlinear relationships among data [*Wilks*, 2011]. Using the first three highest ranked correlation coefficients, linear and exponential regression models were fit to satellite and TSS data. Finally, the MYD09GA data over the in-situ sites of Paudel and Montagna [2014] were extracted. The dataset was filtered following the same procedure as the calibration dataset with the difference that high CHLA was not removed (Figure III-2). This step was omitted as only one data point would have been excluded, and this portion of the data is used for validation only. The high CHL-a content collected in this sample shows how the algorithm is influenced in algal bloom conditions. After filtering had been applied to the validation set, 36 of the 137 data points were left to validate the model. The models' fits for both the calibration and validation datasets were quantified using the Root Mean Squared Error (RMSE) and the R-squared metrics.

5. Results

Table III-1 compares the Spearman rank correlation coefficients between individual bands and band ratios with the TSS collected by the TCEQ. The correlation analysis found that *Rrs* 645, *Rrs* 645/*Rrs*555, and *Rrs* 645 / *Rrs* 469 had the highest correlations with TSS, at 0.65, 0.79, and 0.63, respectively (Table III-1).

Table III-1: Spearman correlations between MODIS bands and band ratios and TSS data (n=56)

Bands	*rho*	*p-value*
Rrs 645	0.65	6.69E-08
Rrs 859	0.42	0.001
Rrs 469	0.11	0.404
Rrs 555	0.16	0.239
Rrs 645 / *Rrs* 859	-0.28	0.041
Rrs 645 / *Rrs* 469	0.63	2.21E-07
Rrs 645 / *Rrs* 555	0.79	9.96E-13
Rrs 859 / *Rrs* 469	0.55	1.35E-05
Rrs 859 / *Rrs* 555	0.44	0.001
Rrs 469 / *Rrs* 555	0.01	0.923

A comparison of empirical methods tested to derive TSS from Rrs are presented in Table III-2. Model fit statistics for the six models considered were compared. The linear regressions and exponential models inputs were based on Rrs 645 and the Rrs 645 / Rrs 555 and 645 / Rrs 469.

Table III-2: Model fit statistics for linear and exponential models for estimating TSS from Rrs and Rrs band ratios .

Fit Type	Band Input	SSE	R-square	Adj. R-square	RMSE
exponential	*Rrs 645 / Rrs 469*	3.88E+04	0.4591	0.4489	27.06
exponential	*Rrs 645*	5.82E+04	0.189	0.1737	33.13
exponential	*Rrs 645 / Rrs 555*	1.37E+04	0.8094	0.8058	16.06
linear	*Rrs 645 / Rrs 469*	3.93E+04	0.4527	0.4424	27.22
linear	*Rrs 645*	5.14E+04	0.2833	0.2698	31.15
linear	*Rrs 645 / Rrs 555*	2.18E+04	0.6969	0.6912	20.26

As indicated in Table III-2, the best model was an exponential function using the band reflectance ratio of *Rrs* 645/ *Rrs* 555. The equation for this algorithm is:

$$y = a*\exp(b*x)$$

Where y is the estimate for TSS in mg/l and x is the *Rrs* 645/ *Rrs* 555 reflectance ratio from the MYD09GA dataset. Coefficients a and b and their 95% confidence intervals were 1.696 (0.7034, 2.689) and, 3.562 (3.03, 4.094), respectively. The model fits quite well to the data with an R-square of 0.8167 and RMSE of 15.7 (n=56) for the SQWMIS calibration data (Figure III-3). The RMSE for the validation dataset is 23.13 (n = 35). Model fit to the data is illustrated in Figure III-3. The uncertainty in this model is estimated to be 13% according to the RMSE compared to the range of the calibrated data. However, more data are needed to get a more robust quantification of error.

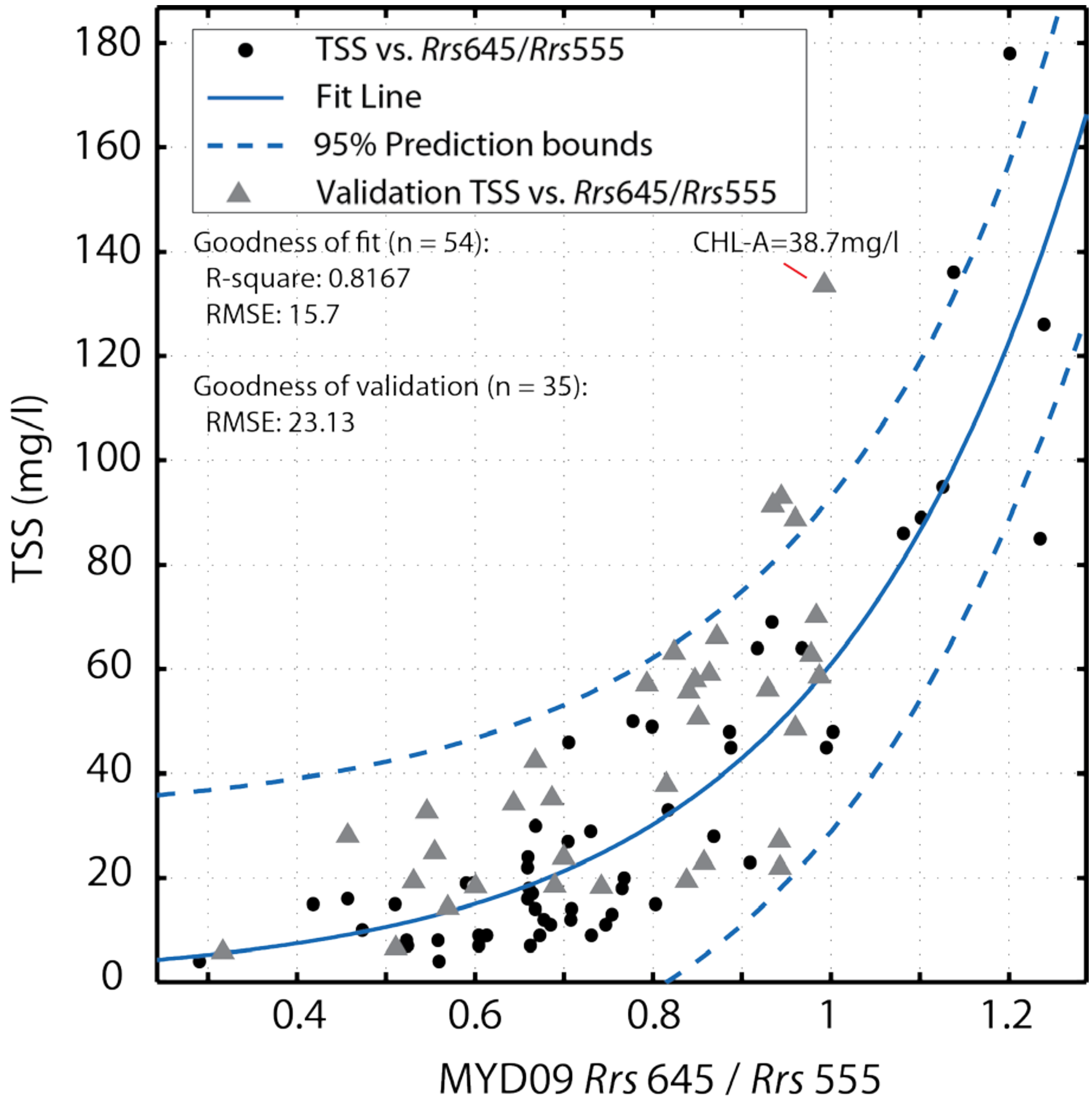

Figure III-3: Model describe in Equation 1 for the estimation of TSS from MYD09 reflectance with in-situ data collected by TCEQ (black circles) and validation dataset (grey triangles) collected by Paudel and Montagna [2014].

6. Discussion

Development of this model enables the creation of synoptic suspended sediment maps in Texas estuaries. This algorithm is a first order approximation of TSS using a reflectance ratio inversion similar to Doxaran et al. 2009. While this model performs well over a range of TSS values and in several Texas estuaries, more validation data is needed to quantify the true error of the model. Individual models for each estuary may reduce the error using the same method used here, but this was not possible due to a lack of in situ data points in each estuary. Other algorithms that use inherent optical properties (IOPs), such as Quasi-Analytical Algorithm created by Lee et al. may provide better estimates of TSS. QAA generates IOPs from *Rrs* which are not dependent on the satellite and solar geometries for which this algorithm is.

As an example, we present data scenes to illustrate different forcings of suspended sediment for Galveston and Matagorda Bays. These images show the ability of the algorithm to show spatial distributions of suspended sediments in these shallow-water estuaries.

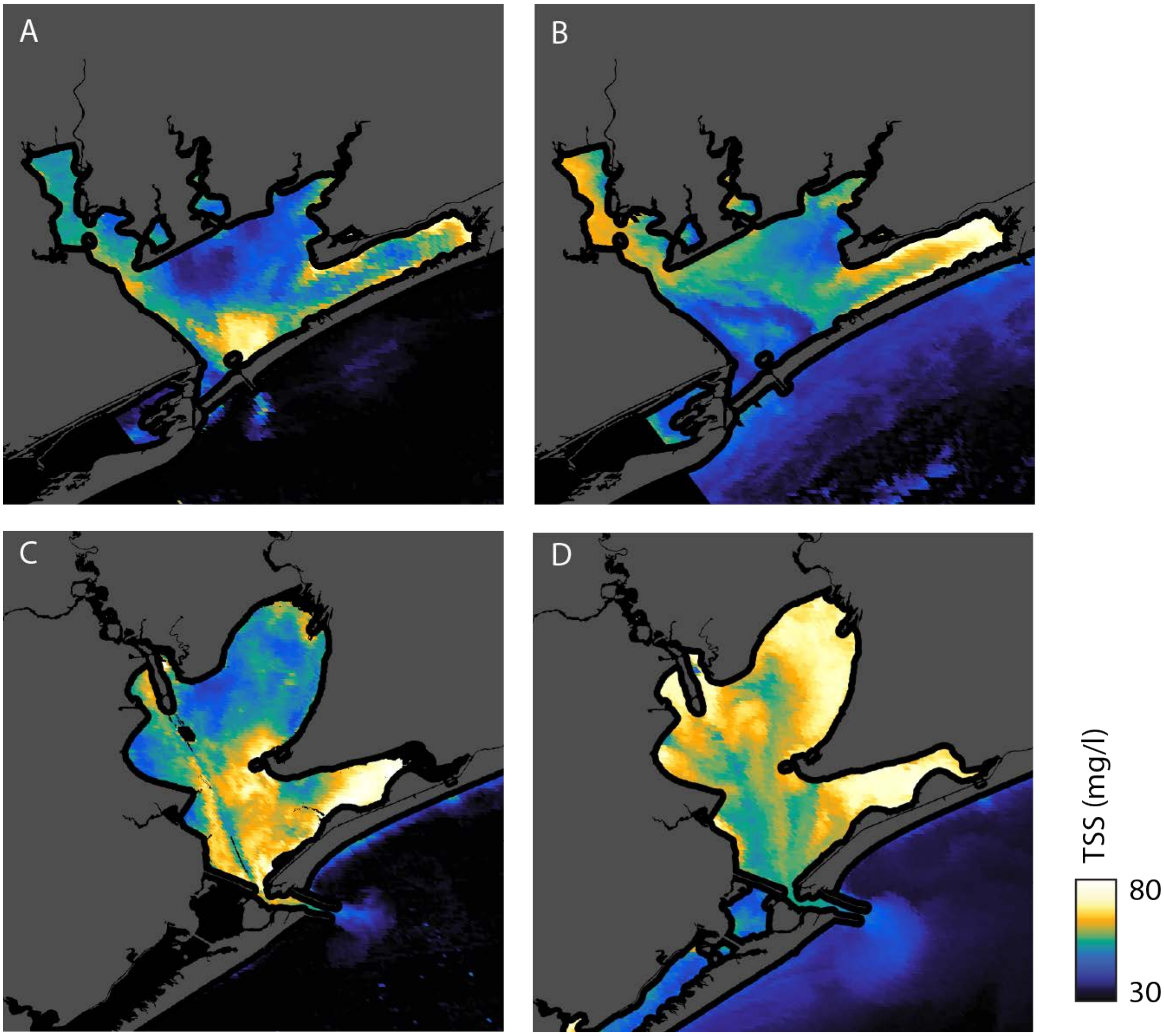

Figure III-4: Examples suspended sediment distributions resulting from different forcings of suspended sediment for Galveston (C & D) and Matagorda (A & B) Bays. (A) resuspension from northern (B) resuspension from southeasterlies. (C) resuspension from northern (D) Plume resulting from high-inflow event coming from the Trinity River.

Usage of this algorithm for deriving TSS from Rrs will cause over -and under-estimations of TSS in high concentrations of CDOM and or CHL-a, respectively. An example is included in the validation data set as illustrated in Figure III-3; in high concentrations of CHL-a the algorithm underestimates the true concentration of sediment in the water. The TSS value 133.7 mg/l occurred during an algal bloom with a CHL-a density of 38.4 mg/l and the models estimate from the reflectance ratio was 59.8 mg/l leaving and underestimation of 73.9 mg/l. While this is a large error, the algal blooms in these estuarine waters are infrequent events with the exception of Galveston Bay's border with the City of Houston [Gonzales 2011]. For the majority of the year, these estuaries are sediment-dominated [Mckee Barman, 1999]. Thus, the influence of algal blooms will only impact the EDR created from this algorithm for a small percentage of the time allowing for analyzes of suspended sediment dynamics in Texas estuaries. The influence of CDOM on the algorithm was not able to be quantified because neither TCEQ nor Paudel & Montagna [2014] collected these measurements.

Lastly, this algorithm may be influenced by bottom reflectance when true TSS values are less than 20 mg/l. However, it is not possible to know without performing radiative transfer modeling for each sample. With these limitations, this algorithm shows promise in creating a TSS EDR for Texas estuaries.

7. Conclusion

A TSS algorithm was created to quantify suspended sediment in estuaries of the Texas Coast. Quantifying suspended sediments in estuarine waters spatially and temporally is key to understanding the morphodynamics of estuarine systems. The creation of this TSS reflectance ratio algorithm using MODIS reflectance data for estuaries of the Texas Coast will be applied to the entire LTDR and a TSS EDR will be created. During the creation of this algorithm, filtering of the data for geometries, sun glint, and water depth was an essential part of developing and implementing this model. Comparison of models found that the usage of an exponential function was the best fit with concentrations ranging from 4 - 176 mg/l. Furthermore, the algorithm was validated with an independent dataset collected by Paudel & Montagna [2014]. The independent data fit well to the model with an RMSE 23.13 n=37. This comparison shows that the algorithm is applicable for usage outside of the period for which the algorithm was calibrated. However, we did find that the algorithm is biased by CHL-a values greater than 30mg/l. Future users of the TSS EDR should be aware of the limitations of the methods. Nevertheless, a TSS EDR was created for the Texas Estuaries Spanning 2002 to 2014.

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CHAPTER IV: SEASONAL SUSPENDED SEDIMENT PATTERNS OF TEXAS ESTUARIES: INSIGHTS FROM 12 YEARS OF SATELLITE DATA

1. Introduction

1.1. Suspended Sediments in estuaries

Estuaries are highly dynamic environments. They exist in transitional zones where riverine systems combine with oceanic systems and exhibit characteristics of both such as floods and droughts, as well as tides and waves. Suspended sediments are an integral part of estuarine systems; their flux within estuaries is a result of interplay between freshwater inflow, tidal currents, wind-wave resuspension, commercial fishing, and dredging operations [*Ward and Montague*, 1996]. The importance that physical processes play in influencing spatial distributions of suspended sediments varies as a function of time and space, morphology, bathymetry, and regional climate, however, the influence of anthropogenic activities is largely unknown [*Ward and Montague*, 1996; *Green and Coco*, 2014]. Suspended sediment flux in estuarine systems contributes to formation and vertical accretion of subtidal and intertidal habitats, food web dynamics, nutrient and pollutant transport, and light attenuation [*Nichols and Biggs*, 1985; *Ward and Montague*, 1996]. Characterizing the movements and spatial and temporal distributions of estuarine sediments provide an insight into their effects on habitats (e.g. flats, salt and brackish marshes, submerged aquatic vegetation, and oyster reefs) both adjoining and within estuaries. These habitats exist in a delicate balance between sediment supply and a variety of other factors. Changes in climate or human alterations to these estuarine systems can influence natural distributions of suspended sediments and thus disrupt habitats within and adjoining the estuarine complex [*Thrush et al.*, 2004; *Ravens et al.*, 2009].

Take, for example, the impact of changes in suspended sediment flux on intertidal habitats such as salt marshes. Salt marshes require sediment input to counter the effects of relative sea-level rise and erosion. Reduction in the amounts of sediment they receive can lead to the conversion of salt marshes to open water [*Brinson et al.*, 1995; *Morris et al.*, 2002; *Ravens et al.*, 2009; *Kirwan et al.*, 2010]. However, when adequate amounts of sediment are supplied to salt marshes, they can keep pace with relative sea-level rise and can spread in areal extent [*Brinson et al.*, 1995; *Kirwan and Guntenspergen*, 2010]. Having abundant amounts of suspended sediment can increase a marsh's resilience to sea-level rise.

Typically, suspended sediment concentrations are quantified by measuring total suspended solids (TSS). This measurement involves taking a volume of water from a point within an estuary and passing through a pre-weighed glass fiber filter [*Texas Commission on Environmental Quality*, 2008]. The filter is then dried and weighed with the mass of the sample divided by the volume of water filtered, normally denoted in mg/l. For temporal studies of estuaries, the sampling is then repeated at the same station over time, thus providing insight into the processes ongoing in the area. Sampling multiple points within an estuary becomes arduous and time-consuming as the number of stations increases with the expanse of the water body studied. Most State and Federal agencies use a few point measurements within estuarine systems to characterize the overall condition of the system[*Ward and Montague*, 1996]. These measurements are not only costly, but also are biased by sampling logistics. Boats are mostly deployed when weather conditions are fair. Thus, samples are biased to fair weather conditions. While these measurements provide much-needed data, their lack of spatial and temporal coverage creates impediments when trying to characterize the complexity and heterogeneity of an estuarine system. Estuaries are highly dynamic environments and the conditions observed at a single point can be the result of many complex and interrelated processes. Thus, the observations may not reflect the system in space or through time [*Ward and Montague*, 1996]. To bridge the spatial gap caused by traditional sampling, Shideler [1984] sampled Corpus Christi Bay using a US Coast Guard helicopter rather than a boat. Shideler was able to sample 14 points throughout the estuary within five hours and produced some of the first quasi-synoptic measurements of suspended sediments in this region. He repeated this sampling methodology a total of eight times and was able to characterize the major spatial patterns of suspended sediment distributions and characterize the bays response to wind-wave resuspension from predominant frontal passages and prevailing southeasterlies.

2. Objective

This research was conducted to gain a better understanding of estuarine sedimentary processes in Texas estuaries using satellite-derived TSS data. Shideler's [1984] research in Corpus Christi Bay is built upon and expanded to Matagorda and Galveston Bays taking advantage of higher spatial and temporal resolution data provided by satellite remote sensing using MODIS-Aqua's almost-daily 500-meter data. These higher spatial and temporal resolution measurements allow for the identification of prevalent and predominated controls that force the distribution of estuarine suspended sediments in shallow-water estuaries[*Booth et al.*, 2000; *Ruhl et al.*, 2001; *Zawada et al.*, 2007; *Doxaran et al.*, 2009; *Feng et al.*, 2014].

The data sets generated for the three major Texas estuaries provide answers to the following questions:

1) What are the dominant forcing(s) of suspended sediments in Texas estuaries?

2) How does the relative importance of fluvial, marine, and meteorological forcing of suspended sediment patterns vary among Texas estuaries?

3) Can the temporal variability of suspended sediment patterns be explained by the climate gradient?

4) Are commercial shrimping and dredging activities important drivers of suspended sediment patterns?

This discussion is organized as follows: first, the coastal environmental setting and estuarine sedimentary processes of the main Texas Bays are described; second, a TSS reflectance ratio algorithm used to create an environmental data record (EDR) of suspended sediments for the study areas from 2002 to 2014 is described; third, TSS composites of seasonal wind and inflow regimes for the three estuaries are generated and compared with their respective forcing and with anthropogenic influences on the TSS patterns; and fourth the dominant processes among estuaries, are compared

3. Study area and its sedimentary processes

3.1. Study Area's Geomorphology and Climate

This study focuses on the three largest estuarine systems in Texas, Galveston, Matagorda, and Corpus Christi Bays (Figure IV-1). The estuaries were chosen because of their size relative to the satellites resolution and location along the Texas climate gradient. Formation of these estuaries is the result of the infilling of Pleistocene river valleys during Holocene sea-level rise [*Davis*, 2011]. They are prime examples of "bar built" estuaries described by Schubel [1971], and are separated from the Gulf of Mexico by a thin strip of barrier islands and spits (Figure IV-1). Small tidal inlets, the majority of which are jettied, connect the estuaries to the Gulf. These estuaries are in a microtidal (0.6 m Gulf tidal range), wave-dominated mixed energy coastal setting, and are affected by a climatic gradient with wetter conditions to the north and drier to the south [*McKee and Baskaran*, 1999; *Davis*, 2011; *Montagna et al.*, 2011]. As a result, average-annual freshwater inflow, normalized by bay volume, decreases 10 fold from north to south. Influence of the Texas climate gradient on freshwater inflow subsequently affects fluvial sediment input to these estuaries. Freshwater inflow into these estuaries carries large amounts of sediments during high-discharge events. Marsh vertical accretion rates and Holocene sediment thicknesses decrease on the bayhead deltas from the Galveston Bay system to the Corpus Christi Bay system [*White et al.,* 2002]. This trend indicates that suspended sediment load carried by rivers decreases from north to south and that freshwater inflow may be relatively more important in the northern estuaries when compared to other inputs of sediments. For all bays, marine sediment input is thought to be relatively small due to the microtidal setting of all the bays [*Yeager et al*., 2006].

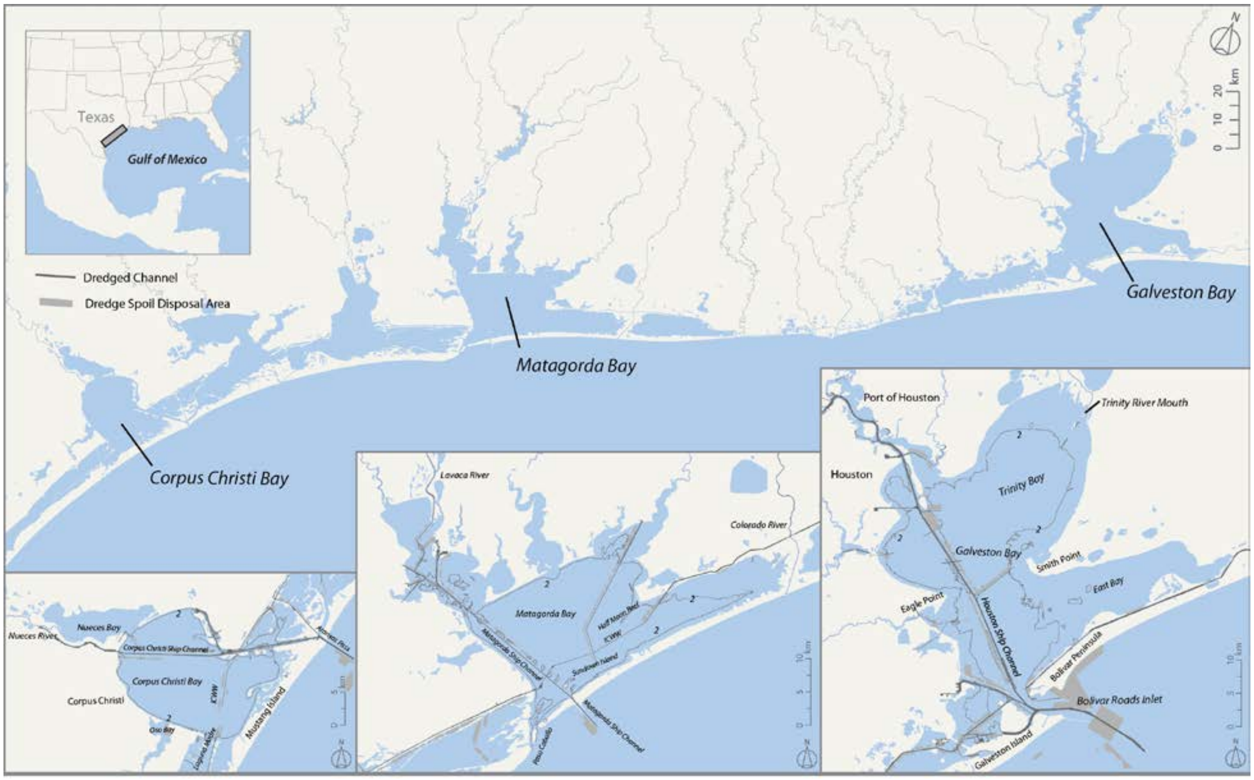

Figure IV-1: Study sites along the Texas Coast with detailed maps of Corpus Christi, Matagorda, and Galveston Bays.

Wind along the Texas coast is prevalently from the southeast for the majority of the year (spring-summer) complemented by predominate northerlies (fall-winter). The prevalent southeasterlies are stronger in the south and decrease in speed moving northeastward along the coast. The wind is strongest during spring and progressively decreases in speed during the summer. In contrast, frontal passages, "northers" or winter storms, bring the dominant wind from the north with wind speed often greater than 15 m/s. During these frontal passages northerly wind gusts are preceded by strong southerly wind speeds [*Ward*, 1997]. Over Matagorda and Corpus Christi Bays, southerly wind speeds is faster than in Galveston Bay. In terms of frequency, the prevalent southeasterlies decrease from Corpus Christi to Matagorda and continue to decrease as you move onward to Galveston Bay (Figures IV-3 - 5).

3.2. Dredging and Related Impacts on the Study Areas

Substantial modifications have occurred within each of the estuaries through the dredging of deep ship channels, 14, 11, and 14 meters deep for Galveston, Matagorda, and Corpus Christi Bays, respectively. These ship channels span the length of each estuary and are maintained for navigation [*Kraus*, 2007]. Other dredged channels are scattered throughout these estuarine systems (Figure IV-1). For example, areas in Corpus Christi and Matagorda Bays are bisected by the Intracoastal water way (ICWW). Galveston Bay's portion of the ICWW only extends for a couple of kilometers. However, other navigation channels cut throughout the estuary.

It is important to note that barge traffic in the ICWW can create plumes of sediment, especially, in Matagorda Bay most likely due to its shallow bathymetry relative to the depth of the channels [personal observation]. Overall dredging activity along the Texas coast is only second to Louisiana in the total annual amount of sediment dredged for channel maintenance [*Walls et al.*, 1994]. Dredging operations suspend the large amount of sediments during the act of dredging but are contained in boomed-off areas that affect small areas. Dredging also has a long-term impact by modifying the bay bathymetries through the deposition of these sediments in placement areas. Both sub- and supra- aqueous sites are used depending on location and cost. Subaqueous placement areas are normally placed adjacent to the ship channel [*Benedet et al.*, 2006]. These sites have shallower bathymetries than their surrounding estuarine areas, and these sediments may be more mobile than other open-water areas. Sediments of dredge spoil disposal sites may have a higher propensity to be suspended by wind-wave action. Supra-aqueous disposal sites, also known as dredge spoil islands can be 5 meters above MSL. These islands can be many kilometers in length and as short as a few meters, and their existence influences the spatial distribution of wind-wave resuspended sediments by influencing fetch length and disrupting downstream wind speed on the leeward side of the island [Markfort - 2010]. The spatial extent of this process depends on the length, height and width of the islands and wind speed.

3.3. Commercial fishing

Commercial fishing activities represent another category of activities with a substantial long-term impact on the Texas estuaries TSS concentrations and distribution. This research includes exploring the relative long-term importance of fishing activities as compared to the other forcing mechanisms. In Texas estuaries, the two main types of commercial fishing activities liberating subaqueous sediments are oyster dredging and shrimp trawling. Shrimp trawls and oyster dredges are dragged across the estuaries bottoms resulting in circular pattern resuspended sediments in the wake of the fishing vessels (Figure IV-2). Commercial Shrimping occurs in all bays with the heaviest fishing pressure in Galveston followed by Matagorda and Corpus Christi [*Montagna et al.*, 2007]. Shrimping activities take place across most of the expanses of the bays. In contrast to shrimping, oyster dredging locations change little in time as the activity is focused on the locations of oyster reefs. It is an important activity in Galveston Bay, less so in Matagorda Bay and is presently not conducted in Corpus Christi Bay.

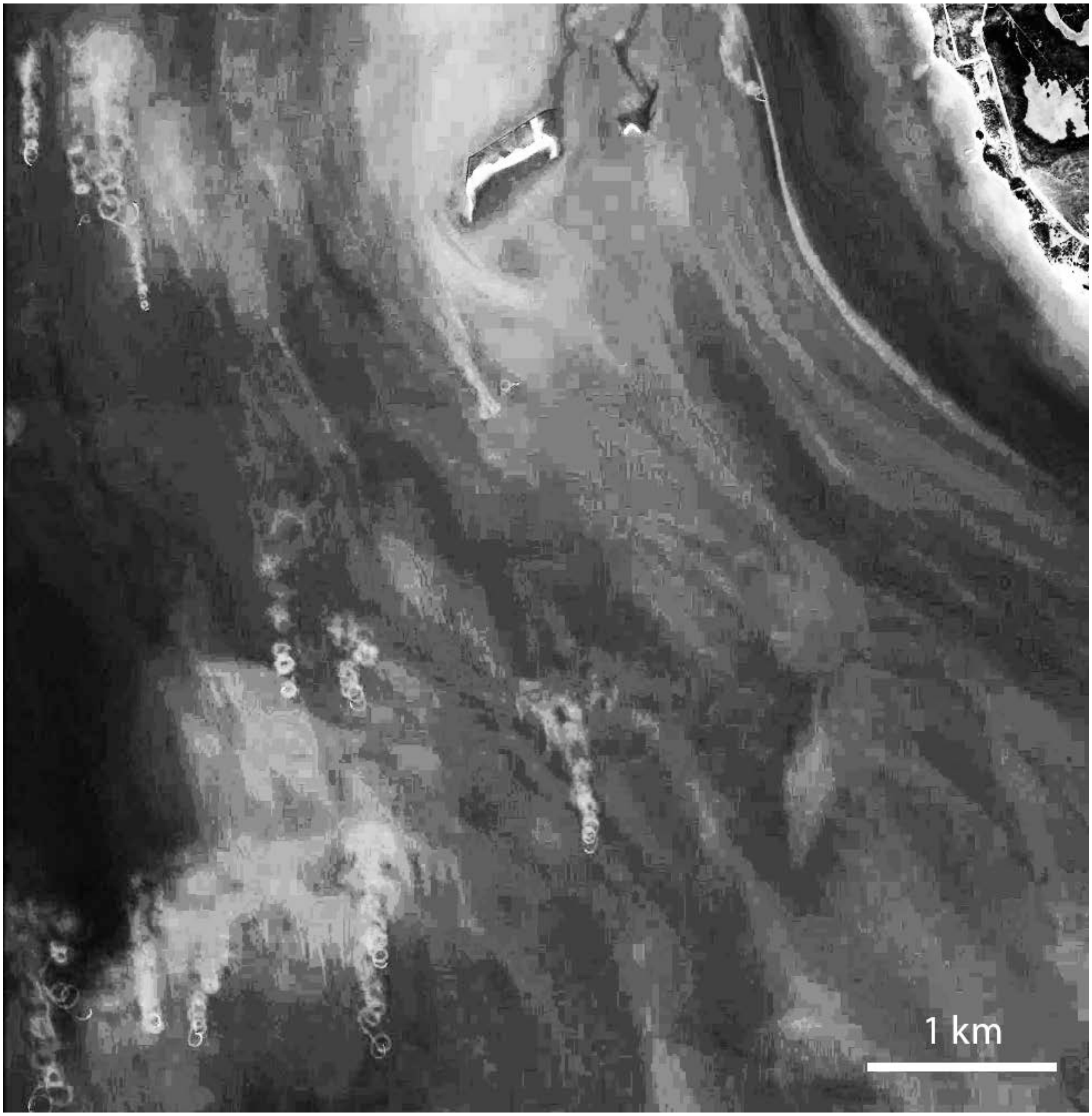

Figure IV-2 Red Band image of oyster boats dredging for oysters off of Smith Point in Galveston Bay March 9th 2009 from USDA imagery.

4. Data and Methods

A TSS reflectance ratio algorithm described in Chapter II was applied to all available scenes of the MODIS-Aqua's MYD09GA reflectance land product over the study areas. These data were downloaded from llpdaas.usgs.gov and totaled 4503 analyzed scenes for this study. Data were then filtered for clouds, sun glint and satellite geometries (outlined in Chapter II), and daily cloud-free TSS maps were created at 500-meter resolution. The portion of cloud free, glint free and geometrically compatible imagery is similar for all bays and represents about a quarter of the number of days for the study period or about 1,100 scenes. Data was incorporated into the time series if only a portion of estuary had data that was cloud-free. Both individual scenes and composites were produced to show suspended sediment patterns in the estuaries. Composite images were generated by computing medians and interquartile ranges (IQR) of satellite-derived TSS data for the entirety of the valid scenes of the satellite dataset. Seasonal comparisons were generated for all estuaries for wind patterns, and for Galveston Bay for inflow regimes, to highlight the respective temporal variability, and show the different distributions and patterns of TSS for the different time periods. Here satellite data within one kilometer of land are removed to avoid mixed pixels of land and water. Also to avoid data contamination from bottom reflectance any data occurring in water shallower than one meter was removed. This depth value was chosen by computing average diffuse attenuation coefficients using the tool provided on the MODIS-Aqua 4-km data product found on NASA's Ocean Color Radiometry Online Visualization and Analysis website for the period of study. Diffuse Atenuation (480) values for Matagorda Bay were 0.545 m^{-1} , in Galveston Bay they were 0.645 m^{-1} and Corpus Christi Bay values were 0.431 m^{-1}.

To investigate wind-wave resuspension, 10-m wind speed data for the study period were extracted from the NCEP's North American Regional Reanalysis (NARR) model [*Mesinger et al.*, 2006] over the three estuaries. The NARRs 32-km spatial and three-hour temporal resolutions were considered sufficient for this analysis. Wind data were analyzed to determine seasonal patterns experienced by these estuaries. Data was split into seasonal wind regimes, and wind roses were plotted and compared to TSS composites for each regime and estuary. The period of November – February is characterized by frontal passages and dominant northerly flows and is referred to as the frontal passages period (FPP). The March-June period is characterized by weaker fronts at the beginning of the period and prevalent southeasterlies, and is referred to as the southeasterly period (SEP). The last period of July-October is also characterized by prevalent southeasterlies, however, their magnitude is lower when compared to the SEP and referred to as the quiet period (QP). Wind data were then plotted as wind roses for each regime and each estuary. Composites of satellite-derived TSS patterns are compared to the related wind rose plots for the three identified wind regimes in Figures IV 3-5 to determine if the wind speed and directional component influences the sediment distributions in the estuaries.

To estimate the importance of inflow, U.S. Geological Survey (USGS) daily stream gauge heights were collected for primary rivers from which these estuaries receive inflow. USGS stream gauges are installed on all of the major rivers. Gauge height measurements were recorded in meters. Gauge height was used instead of discharge data because discharge data at these sites is more sporadic and contains large gaps in temporal data coverage. For Galveston Bay, data were collected from the Trinity River at Livingston, TX, (USGS 08067000); for Matagorda Bay, data for both the Lavaca River near Edna, TX (08164000) and the Colorado at Bay City (USGS

08162500); and for Corpus Christi Bay, data were collected for the Nueces River at Bluntzer, TX (USGS 08211200).

To assess the impact of seasonal inflows in Galveston Bay the dataset was split into a dry (July – Oct.) and a wet (Nov. - June) season. The respective TSS patterns were then compared in Figure IV-6 based on the season's median and IQR TSS patterns. When moving south along the coast, the climate becomes dryer and long-term precipitation patterns become increasingly influenced by events such as tropical storms, and a clear wet/dry delineation correlated with changes in TSS concentration patterns could not be identified for Matagorda and Corpus Christi bays.

5. Results & Discussion

Composite images of TSS median and IQR are presented in Figures IV- 3-5 along with corresponding wind roses created from NARR wind data for each period and for each Estuarine System. Additionally the potential of tidally driven exchanges is discussed for each bay. TSS median and IQR patterns are further compared during the region's dry and wet seasons and the imagery is also analyzed to identify the importance of commercial fishing. Finally, potential limitations of the study are discussed.

5.1. Corpus Christi Bay

The respective TSS composites and wind roses for Corpus Christi Bay are presented in Figure IV-3. During the FPP, median and IQR TSS are higher in the southern portion of the estuary, windward of the predominant north northeast wind direction. Median TSS and IQR values increase as the fetch lengths increase. The similar patterns of both IQR and median TSS with values increasing with fetch length and highest on the windward side of the estuary suggest that wind-wave resuspension from frontal passage is the dominant process controlling suspended sediment concentrations during this period. These patterns are similar to those reported by Shideler [1984] during the same wind regime. TSS median values are the lowest during this period when compared to other wind regimes in this estuary, possibly resulting from the combination of low wind speeds in-between frontal passages and a relatively low frequency of such events. The majority of wind speeds during this period are less than 7.5 m/s (Figure IV-3) while there are typically ten frontal passages during the FPP [Ward 1996]. The low wind speeds in-between frontal passages are likely not significant enough to generate waves that impart sufficient bed shear stress for resuspension as the bay is 4 meters deep on average. While the periods with high TSS concentrations are less frequent than the periods with low concentrations, the high IQR values clearly indicate that significant resuspension occurs during frontal passages. Another area that exhibits a behavior similar to the southern portion of the estuary during the same period are the dredge spoil deposition sites along the ICCW (Figure IV-3,4). Elevated median TSS and more prominently high IQR values as compared to the rest of the bay occur at these locations. Yet these areas fetch lengths are considerably smaller in the direction of the prevalent wind. These areas have more unconsolidated dredged sediments and are shallower than the rest of the estuary thus sediments are more readily resuspended.

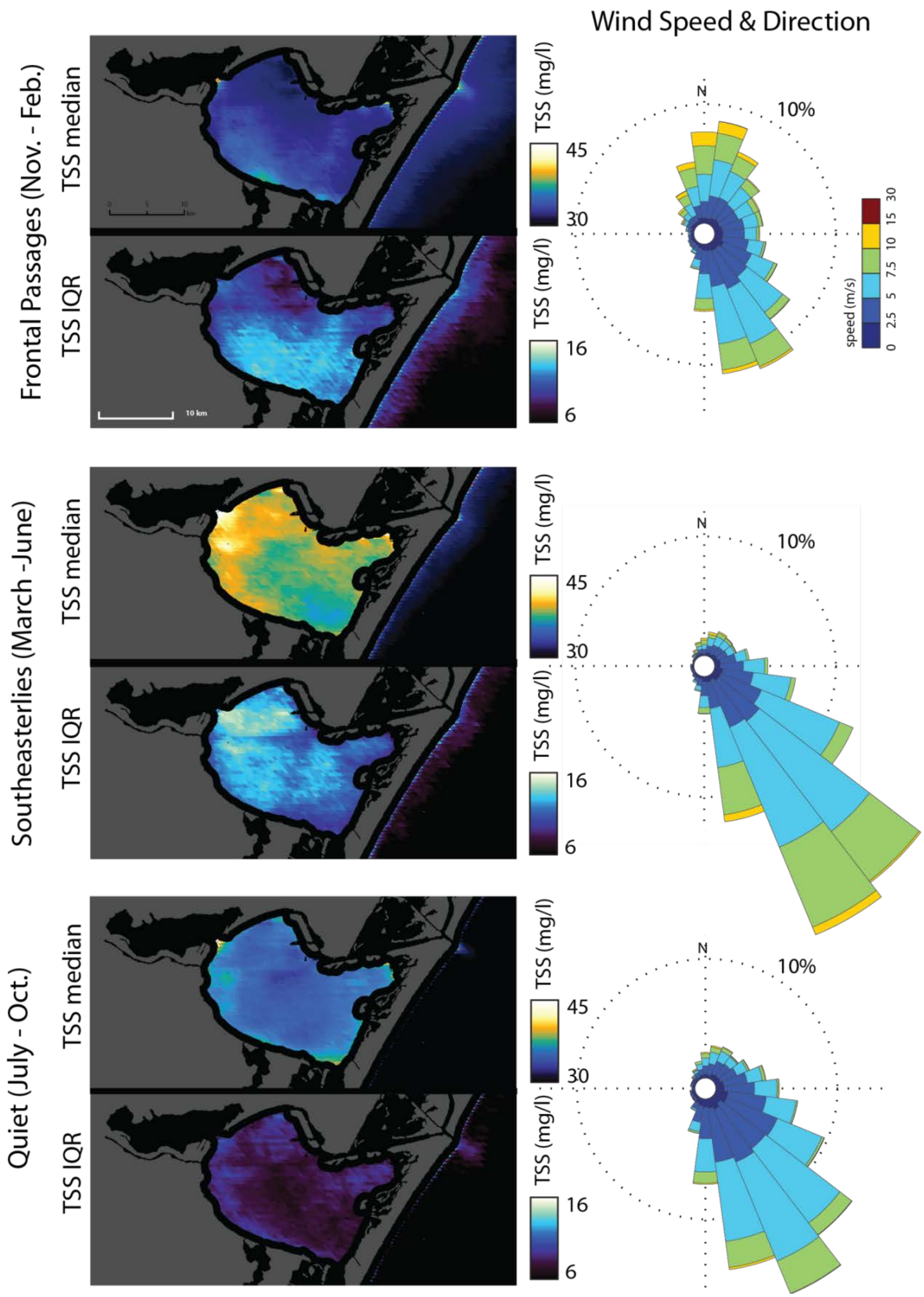

Figure IV-3: Corpus Christi Bay TSS Median and IQR with corresponding wind rose for each wind regime

Another factor that may influence the measured patterns is biased due to cloud presence [*Eleveld et al.*, 2014]. The higher wind periods may be under-represented as compared to the actual resuspension events that occur because the majority of cold fronts are accompanied by cloud-cover that obscures the satellites view of the estuary.

The FPP composites of Corpus Christi Bay also support Shideler's [1984] hypothesis that Nueces Bay is a fluvial sediment storage basin having a control valve activated by strong northerly wind. Suspended sediments are released into Corpus Christi Bay during frontal passages as indicated by the higher median and IQR TSS values near the entrance to Nueces Bay. As compared to those of the surrounding area, consistent with resuspended sediments spilling into Corpus Christi Bay when strong wind is blowing for a prolonged period from the north.

The influence of tides is more difficult to identify using the composite patterns, however, some observations can be made. Lower IQR values are observed along the length of the Corpus Christi Ship Channel (Figure IV-3). Additionally, median and IQR values are lower than surrounding values at the entrance of the Corpus Christi Ship Channel into the main portion of the bay. Both observations are consistent with flood plumes that are lower in suspended sediment concentration originating in the Gulf of Mexico. These lower values indicate that, for Corpus Christi Bay, tidal flux reduces the concentration of sediment in the bays, however, the tidal force influence is spatially limited. Export of suspended sediments from the Bay to the Gulf of Mexico is also evident from an ebb plume at the exit of the ship channel into the Gulf of Mexico (Figure IV-3). While an exchange of suspended sediments with the Gulf of Mexico will also depend on wind-driven transport, such exchange can be observed for all wind regimes, including during the quiet period indicating that tidal transport is significant. Other TSS concentrations along the Gulf of Mexico shorelines are observed for the FPP period consistent with the northerly wind direction of the fronts while TSS concentrations for the other periods are much smaller nonexistent.

The southeasterly period has the highest concentrations of median and IQR TSS values when compared with the three wind regimes. Similarly to the FPP, both Median and IQR TSS values increase along fetch length in the dominant wind direction. Highest median and IQR TSS values are located along and near the windward shore in the northeastern quadrant of Corpus Christi Bay. This area is where the predominant and prevalent wind of this wind regime have the longest fetch lengths, approximately 18 kilometers. Similarly to the FPP, this pattern indicates that wind-wave resuspension is the dominant process influencing estuarine suspended sediment distribution during this period. The median TSS composite resembles the pattern in Shideler's [1984] southeasterly mode. Similar to Shideler's [1984] observations, the southeastern quadrant of Corpus Christi Bay has very low concentrations of TSS. These low TSS concentrations are attributed to a flux of sediment free waters from the Upper Laguna Madre being pushed into the southern portion of Corpus Christi Bay by the southeasterly wind.

Dredge spoil deposition sites exhibit similar behavior to those during the FPP. The dredge spoil area located on the ICWW have higher median and IQR TSS values than surrounding area. These higher values in both FEP and SEP illustrate that these areas are more prone to wind-wave resuspension. The dredge spoil deposition site next to the entrance of the port of Corpus Christi, also has higher median and IQR values than those of the surrounding area.

During the QP period, the Corpus Christi Bay median and IQR values are relatively uniform. Areas near and along the windward shore have slightly elevated values when compared to the rest of Corpus Christi Bay. The low concentrations of median and IQR TSS values indicate that waves resuspended less sediment than during any of the other time periods. The IQR pattern also displays the lowest values indicating consistently low TSS concentrations during the QP. The highest concentrations of median TSS values are located over the dredge spoil deposition area near the Port of Corpus Christi similar to during the SEP.

5.2. Matagorda Bay

Similar to Corpus Christi Bay, during the FPP suspended sediment concentrations are higher in the southern portion of the estuary and along the windward shore of the predominant north northeast wind direction. Median TSS concentrations increase as fetch lengths increase following the direction of the prevalent north, northeastern wind, however the increase is not very apparent as the gradient only increases from 34 mg/l to 38 mg/l in Figure IV-4. Similarly to Corpus Christi Bay, this pattern results from episodic frontal passages resuspending sediment, and the estuary has relatively little wave action in periods outside the frontal passages. The IQR composite shows high values in the middle of the estuary. The overall pattern is consistent with a convolution of prefrontal and postfrontal resuspension events due to wind-waves. Evidence of the combined influence of pre- and postfrontal resuspensions explains the lower IQR values leeward of Sundown Island in the direction of the prefrontal southeasterlies Figure IV-4, as compared to those of the adjacent areas not shielded by Sundown Island for such wind direction. These areas have higher IQR values as they are resuspended by both prefrontal and postfrontal wind-waves processes, while the area to the northwest of Sundown Island is resuspended only by post frontal wind-wave events , thus creating the shadow in the IQR composite.

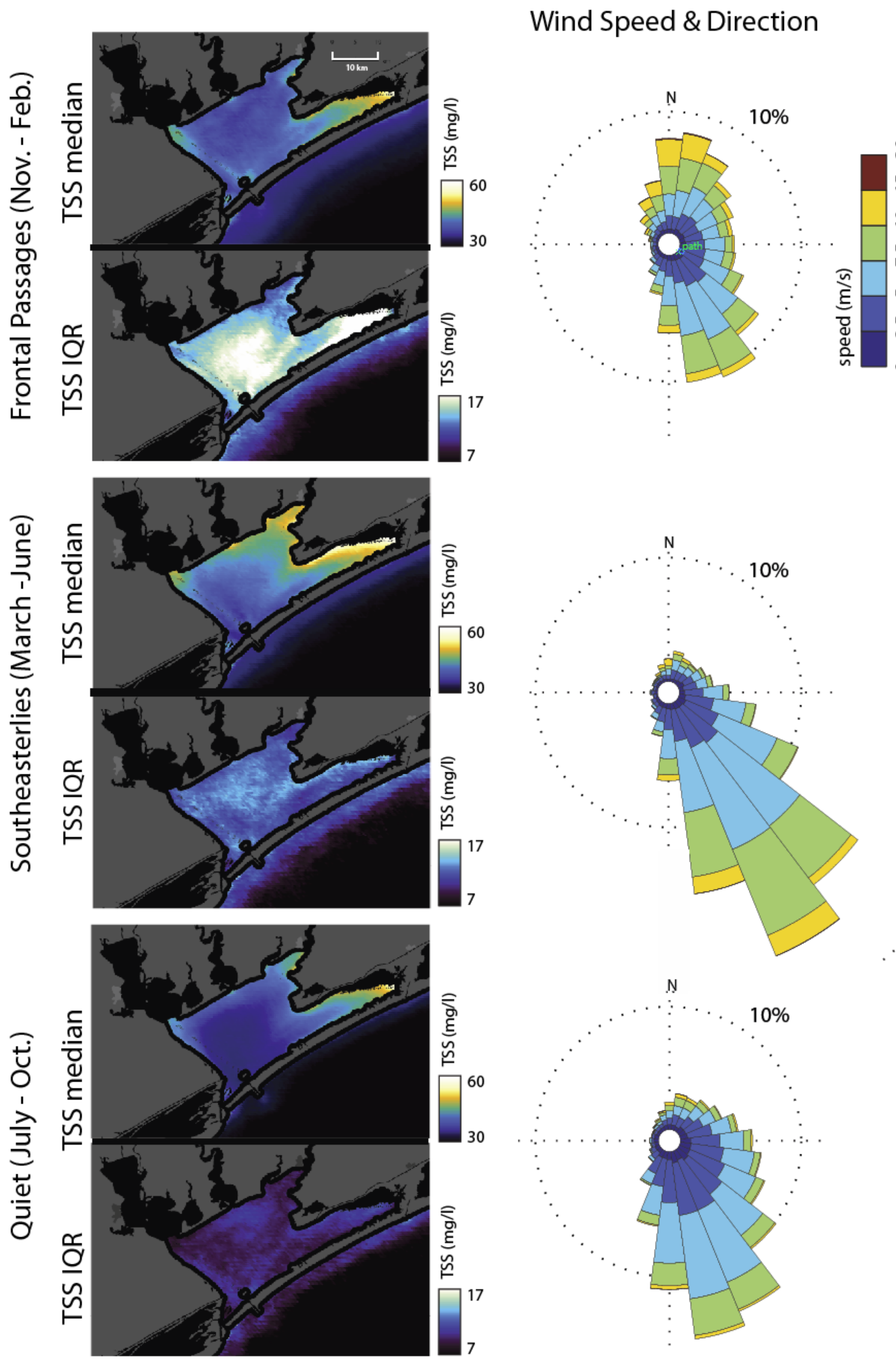

Figure IV-4: Corpus Christi Bay TSS Median and IQR with corresponding wind rose for each wind regime

Postfrontal wind influences the TSS concentrations along the Gulf of Mexico shorelines as shown by the median and IQR patterns in Figure IV- 4. Offshore the extent of the TSS IQR and median values are also larger around the inlets mouths than the rest of the nearshore in front of Matagorda Island. This overall plume pattern indicates the offshore current is in the southerly direction. Large amounts of sediments that are resuspended during frontal passages are transported into the nearshore and carried along the coast to the southwest.

Another feature that is commonly seen in Matagorda Bay is the sediment resuspended from barge traffic up and down the ICWW (personal observation in the field and from higher resolution satellite imagery). The linear feature shows up there along the length of the ICWW channel. Low median TSS values in the estuary during this period allow for the linear feature of resuspended sediment created from propellers of barges to be more pronounced.

For Matagorda Bay, median, TSS composites show the highest concentrations during the SEP as compared to the other wind regimes. The IQR values are however lower than during the FPP indicating that the bay experiences high TSS concentrations more consistently during this period. Similar to Corpus Christi Bay for the same wind regime median TSS values increase along fetch length. The center of the estuary has the highest IQR values windward facing shorelines, and shallow water area have the highest median concentrations and lower IQR values. These patterns indicate that the shallow areas experience higher wave energy, thus, resuspending bottom sediments more frequently. Areas like Half Moon Reef, which is shallower than the areas surrounding it, also experience more frequent resuspension of sediment than deeper parts of the bay. Another process affecting spatial distributions of sediment during this period is topographic shadowing. Like during the FPP, Sundown Island disrupts the wind field of the prevalent southeasterlies, and its effect is observed in both median and IQR composites northwest of

Sundown Island in the lee of the dredge spoil island. Overall the median TSS composites pattern resembles those of the suspended sediment pattern generated from hydrodynamic models in Pandoe & Edge [2008] for the same wind direction.

During the quiet period, patterns similar to the SEP patterns are observed but with less sediment in suspension due to less frequent and weaker wind speeds. During the QP period, the MB median and IQR values are relatively uniform. Areas near and along the windward shore have slightly elevated values when compared to the rest of the bay. The low concentrations of median and IQR TSS values indicate that waves resuspended less sediment or less frequently than during any of the other time periods.

5.3. Galveston Bay

In Galveston Bay, median and IQR values are the highest among wind regimes during the FPP, the period during which wind speed and riverine inflows are the highest (Figure IV-5). The most distinct pattern is the linear feature in the median TSS composite around Smith Point continuing southward toward the western end of the Bolivar Peninsula. The predominant wind fetch lengths here is greater than 25 km in length and are some of the longest fetch lengths for this wind regime. Evidence of the fetch's influence on median TSS concentrations is further observed to the east of this linear feature. There lower TSS concentrations occur as the topography of the paleo-Trinity River Delta shortens the fetch length. The far eastern corner of East Bay has the highest TSS value; however these are most likely due to high CDOM transported from Sabine Lake via the ICWW. High CDOM concentrations cause overestimates of TSS values due to the nature of the reflectance ratio algorithm. While no in-situ data exist to confirm the high CDOM concentrations, high median TSS values along with relatively low IQR values are observed for all wind regimes for this area reinforcing this analysis.

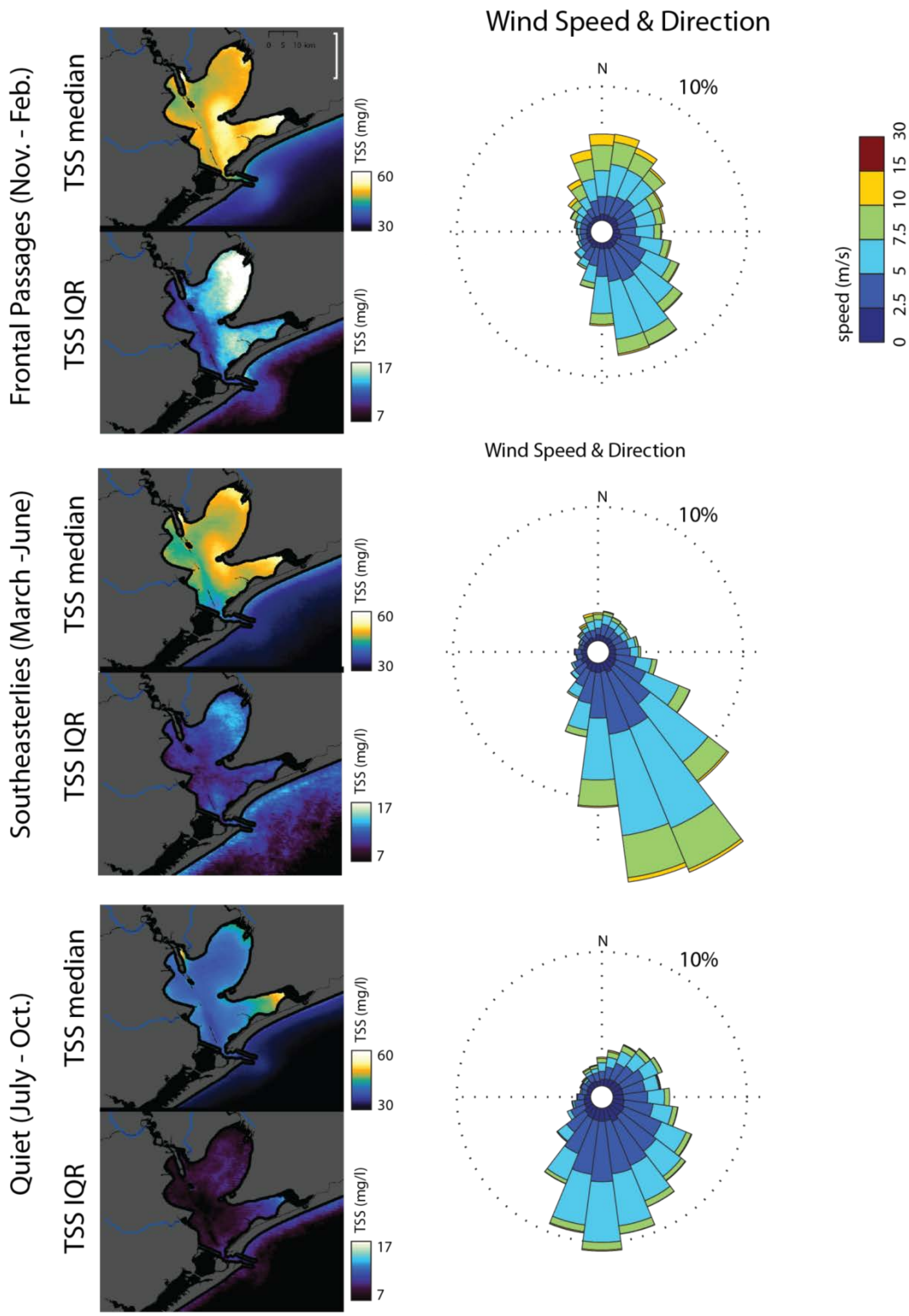

Figure IV-5: Galveston Bay TSS Median and IQR with corresponding wind rose for each wind regime

While the fetch length explains in part the high median TSS values around Smith Point, these values are higher than median TSS further south where the fetch lengths are even longer (see Figure IV-5). This is most likely due to oyster harvesting during times of lower wind speed and lower wave action in-between frontal passages when fishermen take advantage of calmer waters. Texas oyster season spanning November 1st to April 15th is ongoing throughout this wind regime. Smith Point's IQR values are low most likely because of the combination of frequent oyster dredging and cold front passages leading to consistently high median values. The higher IQR values observed further east from Smith Point are due to the variable freshwater plume from the Trinity River, see Figure IV-5.

Another area with an interesting feature is Trinity Bay with high median TSS values and the highest IQR values. The southeastern side of Trinity Bay has higher median TSS concentrations as compared to the northwestern half of the bay. These high concentrations are, however, due in large part to the river plume, discussed later in this section, combined with wind wave resuspension, as high discharge from Trinity River occurs during this wind regime. However, wave resuspension from frontal passage is not the controlling factor of the variability in this section of Galveston Bay. For this bay, the FPP period spatial variability is dominated by freshwater inflow, that is evident by the size and location of the high IQR area in Figure IV-5 matching well the extent of the river plume. As expected, beginning at the mouth of the Trinity, IQR values decrease as a function of distance further indicating that variability is dominated by inflow. This IQR pattern also indicates that the plume spatial extent varies.

Lower median TSS concentrations are observed in the area around the Port of Houston. This lower computed concentration of median TSS is most likely the result of frequent algal blooms rather than actual lower TSS concentrations. This area is prone to algal blooms as this area is highly urbanized and recives nutrient runoffs and effluents from several sewage treatment plants [Gonzalez, 2011]. Evidence of algal blooms is also visible in both true color MODIS imagery and TCEQ SWQMIS Chl-a concentrations. High CHL-A concentrations bias the TSS algorithm into predicting lower TSS values as discussed in Chapter II.

The Bolivar Roads inlet plume's extent, variability, and concentration are greatest during the FPP period as compared to the other wind regimes, most likely due to metrological ebb tide carrying resuspended sediments into the Gulf. The extent of the resulting water exchange between Galveston Bay and the Gulf during frontal passages has been described by [*Ward*, 1991]. Ward showed that two-thirds of the volume of the bay could flow through the inlet during a frontal passage. This pattern mimics that of Matagorda Bay during the same wind regime. The shape of these estuaries and inlet locations relative to prevalent wind permits for large amounts of resuspended sediments to be transported out to the Gulf of Mexico from meteorological flood tide from the water level step-up created from these frontal passages.

Similarly to the other bays, the Houston ship channel has lower values of median and IQR values indicating that resuspension does not occur in the channel combined with a marine influx of lower TSS waters during flood tides but the effect remains localized to the Channel. Tidal influence on the bay TSS concentrations outside of the ship channel was not identified in Galveston Bay.

TSS median values are highest along the windward shoreline on the margins of the estuary as compared to those downwind of the predominant northerlies. This pattern is especially visible east of Eagle Point.

While areas of higher median TSS concentrations are observed in the northeastern portion of Galveston Bay and around Smith Point, these areas are not consistent with the expected impact of strong southeasterly wind. The northwestern shores of the Bay show lower concentrations and little variability. Overall there is no definitive evidence of prevalent southeasterly wind on the estuary during this wind regime This is in contrast with observations from the two previous bays where there is windward shoreline resuspension evident like patterns. Patterns may not be evident due to the lower wind speeds and frequency of strong (> 5m/s) wind. Also, the signal resulting from riverine inflow may overshadow the wind/wave influence as compared to other bay systems. Similarly to the FPP period, a salient pattern is evident surrounding Smith Point and to a smaller extent off Eagle Point. The pattern is identified as a signal from oyster dredging at both locations. Even though oyster season occurs for two months during this period, its prevalence is highlighted by the High concentrations in Oyster harvest in both areas.

During the QP GB, median sediment concentration is relatively low and uniform, similar to CCB during the same period. Noticeably missing is the oyster harvesting signal. Oyster harvesting does not overlap with the QP period, and this is clearly evident in the composite Figure IV-5. Oyster harvesting still has slightly higher median TSS values that are possibly due to more liable sediments on the oyster beds. During this wind regime, the highest median and IQR values are on the east side of East Bay. Both Median and IQR values decrease as a function of distance from the entrance of the ICWW into East Bay indicating that the source of high CDOM water is from the Sabine Lake system. Similarly to the other bays and other wind regimes a somewhat lower medians and variability are observed in the Houston ship channel. Offshore of the bay, the ebb plume median TSS values and extent is greatly reduced when compared to the other wind regimes.

5.4. Wet and Dry period for Galveston Bay

A substantial difference between Galveston Bay and the other two bays studied is the influence of the riverine input on the bays TSS concentrations. The influence of freshwater inflow to the GB estuarine system is further studied in Figure IV-6. For this portion of the discussion the data set is now split between a dry (July-Oct.) and a wet season (Nov.-June) based on the gauge height values for the Trinity River (see Figure IV-6). Wet season median and IQR composites show the large riverine influences on Trinity Bay. The plume created by the Trinity River is especially apparent in the IQR composite, as IQR values decrease as a function of distance from the river mouth. Higher values of median and IQR occur on the southern edge of the bay as it is the typical flow path for the plume. The oyster harvesting signal is also prevalent during this period as it is concurrent with the wet period. The Galveston Bays dry season has low values of both IQR when compared to the wet season, and median values of TSS near the mouth of the Trinity River indicating inflow is not controlling sediment distributions during this season.

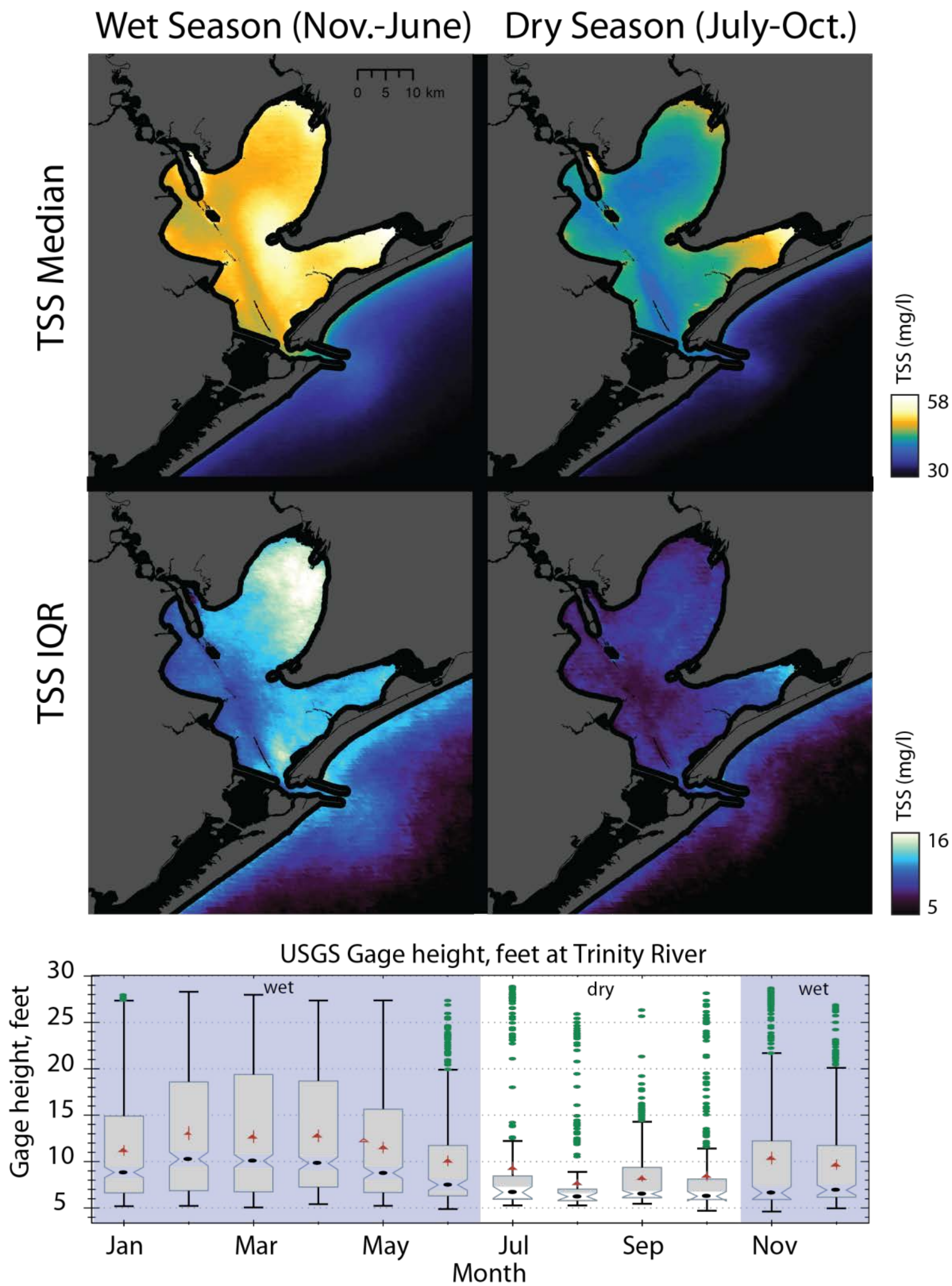

Figure IV-6: Galveston Bay TSS Median and IQR with corresponding seasonal box plot for Gage Height at the Trinity River in Liberty, Texas

6. Potential Limitations of the Study

While closing the discussion it should be reminded that the median TSS composites may be biased by cloud presence obscuring satellite view of estuaries and thus providing lower representation of scenes associated with frontal passages, southeasterlies, sea breeze, and thunderstorms. While these biases likely influence total estimated suspended sediment concentrations, the overall seasonal changes in resuspended sediment concentration patterns are unlikely to be substantially affected by these biases and are still clearly identifiable permitting assessment of the importance of the respective forcing mechanisms.

Cloud bias may also play a role when comparing the respective resuspended sediment concentrations among the three bays. The climate gradient changes from higher precipitations around Galveston Bay to a dryer climate for Corpus Christi Bay while median wind speed during southeasterlies are higher in Corpus Christi Bay as compared to Galveston Bay. The climatic differences affect cloud patterns and hence are likely to lead to different cloud-related biases. This limitation prevents a precise comparison of median observed resuspended sediment concentrations among the bays but does not affect the comparison of the patterns and their seasonal variability and main forcings. Another potential limitation of this study is the influence that CDOM, and high CHL-a have on the reflectance ratio algorithm. Areas with high CDOM concentrations will overestimate TSS concentrations while areas of high CHL-a underestimate TSS concentrations.

Finally, sediment sizes and types differ between bays influencing the spectral signature of the reflected signal. The algorithm used to quantify TSS for this study assumed similar sediments in all bays and is an approximation, with the main goal to elucidate the TSS patterns. Moreover, the potential for resuspension and the depth influence of the critical wind speed necessary for the onset of resuspension may be different among bays due to these differences in sediment types.

7. Conclusion

This study investigated the relative importance of freshwater inflow, tidal currents, wind-wave resuspension, commercial fishing, and dredging operations on suspended sediment long-term variability in the three largest estuarine systems in Texas, (Galveston, Matagorda, and Corpus Christi Bays). The usage of a TSS EDR permits the comparisons of TSS composites for seasonal wind and inflow regimes in each estuary and permits the identification of dominant forcing(s) of suspended sediments in these estuaries.

The Galveston Bay system is to be dominated by riverine inflow with some influence from frontal passages. Surprisingly, we found that influence of oyster harvesting in Galveston Bay was the most salient pattern within the estuary. Matagorda Bay patterns indicate that the system is mostly controlled by wind-wave resuspension with patterns changing between frontal passages and southeasterlies-dominated seasons. Corpus Christi Bay is similarly influenced by wind-wave resuspension with different patterns during the predominant northerlies and prevalent southeasterlies seasons. TSS are lower in Corpus Christi Bay compared to Matagorda Bay with the difference attributed to shallower average depths and longer fetch lengths in Matagorda Bay. The impact of dredging is also apparent in long-term patterns of Corpus Christi Bay as concentrations of suspended sediments over dredge spoil disposal sites are higher and more variable than surrounding areas, which is most likely due to their less consolidated nature and shallower depths requiring less wave energy for sediment resuspension.

Ship channels influence resuspended sediment concentrations in all bays due to reduced suspended sediment concentrations associated with the enhanced exchanges with the less turbid waters of the Gulf of Mexico and higher water depth, i.e. not a direct source of resuspended sediments.

This study also highlights the advantage of synoptic measurements, that permits the identification of commercial fishing as a source of sediment resuspension when compare to the result. The harvesting of oysters around marshes could increase the amount of suspended sediment being supplied to the marshes and may help them keep up with sea-level rise.

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CHAPTER V: CONCLUSIONS

1. Conclusions

Suspended sediments are an integral part of estuarine systems in that they impact water quality and form habitats; their flux is a result of interplay between freshwater inflow, tidal currents, wind-wave resuspension, commercial fishing, and dredging operations. This dissertation investigates the relative importance of the aforementioned drivers of suspended sediment in the three largest Texas estuaries (Galveston, Matagorda, and Corpus Christi Bays) using two different methods of analyses. The first method employed statistical analysis of point measurements of total suspended solids (TSS) collected by the Texas Commission on Environmental Quality and environmental forcings. Relationships of TSS data and environmental forcings were quantified using correlation and variable importance analyses. To bridge the spatial and temporal gaps inherent within the TCEQ dataset, an algorithm was created to transform reflectance measurements from satellite images into TSS. The algorithm was used to create a TSS time series for each of the aforementioned bays for the period of 2002-2014. From this time series median and IQR composites of suspended sediments were generated for seasonal wind and inflow regimes in each estuary. These data were then compared to environmental forcing data.

The two methods permit different types of analyses. The satellite-derived concentration maps permits the identification of seasonal patterns of suspended sediment concentrations leading to identification of the relative importance of forcings within each of the estuaries. The statistical analysis of point measurements permits for a more quantitative comparison of the different forcings impact on suspended sediment concentration by performing correlation and variable importance analysis. While satellite data provide for the first time the ability to perform synoptic analysis of TSS patterns in Texas Bay, inherent limitations of the method include the precision of the calibration process making it difficult to quantify actual sediment concentration and cloud biases. Alternatively point measurements provide accurate sediment concentrations however the information derived from this data is strongly influenced by the location of these observations and their temporal and spatial coarseness as well as biases from navigation conditions. This dissertation's conclusions benefit from analyses based on both approaches characterization of TSS in Texas estuaries.

For Corpus Christi Bay, both analysis methods show that wind-wave resuspension is the dominant forcing of suspended sediments. The satellite data permit the identification of patterns characteristic of the different wind regimes, as well as, the influence that subaqueous dredge spoil areas have on the concentrations of suspended sediment. Both analyses show that wind-wave resuspension is the dominant forcing of suspended sediment in Matagorda Bay as well. The point data analysis shows that tidal forcing is also important for this bay's sediment concentrations. For the same wind regimes Matagorda Bay has higher suspended sediment concentrations and variability (IQR) than Corpus Christi Bay due to shallower bathymetry and longer fetch lengths. This conclusion is consistent with the results of the correlation analysis of the point data showing that Matagorda TSS has a higher correlation coefficient with the wind-wave proxy as compared to the other bays. Both analysis methods show that freshwater inflow is important in Galveston Bay, however the point data analysis may underestimate the relative importance of fresh water inflow due to the coarse spatial and temporal resolutions. The higher resolution of the satellite-based analysis permits the identification of the spatial extent of the freshwater inflows influence on suspended sediments and the temporal variability of this influence. The analysis shows that wind forcing is relatively not as important in Galveston Bay as compared to the other estuaries. Surprisingly, we found that the influence of oyster harvesting in Galveston Bay is the most salient pattern within the estuary.

This study highlights the advantage of how long synoptic time series of TSS can be used to elucidate the major drivers of suspended sediments in estuaries as well as their seasonal variability. The methods and results will guide ecologists and geologists who are modeling habitats, e.g. essential fish habitat, marshes, and, oyster reefs and provide insight into where mitigation and restoration efforts should be focused.

BIOGRAPHICAL STATEMENT

Anthony S. Reisinger was born in Brunswick, Georgia. His family then moved to Harlingen, Texas where he was raised. He attended The South Texas Science Academy for high school, and then attended the Texas State Technical College where he obtained his Associate of Applied Science, Digital Imaging Technologies in 2002. Later, he attended The University of Texas at Brownville where he was awarded the Ernest Hollings Scholarship from NOAA. He worked at NOAA for an internship at the NOAA Environmental Visualization Laboratory and then graduated with a Bachelor's of Science in Environmental Sciences from the University of Texas at Brownsville. In 2008 he came to Texas A&M Corpus Christi to work with Dr. James C. Gibeaut. During his time at TAMUCC, Anthony received a graduate fellowship from National Aeronautics and Space Administration (NASA) Earth and Space Science Fellowship to finish this dissertation.