EFFECT OF CLIMATE ON ESTUARINE BENTHOS AT REGIONAL SCALES ALONG THE TEXAS COAST

A Thesis

by

MEAGAN NICHOL HARDEGREE

BS, Texas A&M University- Corpus Christi, 2015

Submitted in Partial Fulfillment of the Requirements for the Degree of

MASTER'S DEGREE

in

ENVIRONMENTAL SCIENCE

Texas A&M University-Corpus Christi
Corpus Christi, Texas

May 2018

EFFECT OF CLIMATE ON ESTUARINE BENTHOS AT REGIONAL SCALES
ALONG THE TEXAS COAST

A Thesis

by

MEAGAN NICHOL HARDEGREE

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

"Paul Montagna, PhD"
Chair

"Jennifer Beseres Pollack, PhD"
Committee Member

"Toshiaki Shinoda, PhD"
Committee Member

May 2018

ABSTRACT

Climate variability plays a key role in estuary structure and function. Fresh water is delivered to estuaries as inflows driven by precipitation. The amount of precipitation an area receives could be affected by climate change. Precipitation along the Texas coast is variable from year to year and linked to the El Niño Southern Oscillation (ENSO). A previous study demonstrated decreasing long-term trends in benthos abundance and biomass in response to changes in hydrologic conditions in the Lavaca-Colorado Estuary. The purpose of this study is to investigate whether the previous findings are unique to the Lavaca-Colorado Estuary or if these effects are regional in scale. Six stations in the Lavaca-Colorado Estuary, four stations in the Guadalupe Estuary and five stations in the Nueces Estuary, representing a salinity gradient in each estuary, were sampled quarterly for benthic macrofauna and hydrography from 1986-2009. The Ocean Nino Index (ONI) was analyzed for relationships between estuarine conditions and climate. In all three estuaries, ONI was positively correlated with salinity, inflow and dissolved oxygen. Long-term declining trends in benthos abundance were found in all three estuaries; however, biomass trends varied by bay system. A second purpose was to compare infauna and epifauna trends. Epifauna data was obtained by the Texas Parks and Wildlife Department. In some of the bays, benthic abundance and biomass was positively correlated with trends in epifauna, which are potential infauna predators. Epifauna abundance and benthic abundance were correlated with bay salinity, temperature and dissolved oxygen (DO), so overall, infauna and epifauna had similar responses over time. In contrast inverse responses would be expected if epifauna preyed on infauna, so climate change appears to be the dominant driver of long-term trends in both groups.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Paul Montagna, and my committee members, Dr. Jennifer Pollack, and Dr. Toshiaki Shinoda, for their guidance and support throughout the course of this research. I would also like to thank all the members of the Ecosystem Modeling Lab, especially Larry Hyde, Rick Kalke, Elani Morgan, Jamie Smith, and Noe Barrera, and extend my gratitude to two former members of the Ecosystem Modeling Lab Crystal Chaloupka, and Meghan Hargis who helped process six years of archived Nueces Estuary samples.

Thanks also go to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University-Corpus Christi an enjoyable experience. I also want to extend my gratitude to my friends, and family for their love and support during my time as a graduate student.

The Rachael and Ben Vaughn Foundation provided partial support for this study to Dr. Paul Montagna.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURES PAGE

LIST OF TABLES

INTRODUCTION

Climate variability plays a key role in estuary structure and function. Freshwater is delivered to estuaries as inflows driven by precipitation. The El Niño Southern Oscillation (ENSO) is a naturally occurring phenomena that involves fluctuating sea surface temperature (SST) in the Pacific Ocean. These temperature fluctuations influence atmospheric and oceanic conditions over large parts of the globe (Rasmusson & Carpenter 1982; Gershunov & Barnett 1998). ENSO teleconnections originate from the seasonal cycle of jet streams and have been associated with seasonal mean anomalies in temperature and precipitation across North America (Rajagopalan et al. 2000). The warm phase of ENSO is known as El Niño and the cool phase of ENSO is known as La Niña.

Texas precipitation patterns are characterized by low base flows, with intervals of large inflow events from frontal activity and tropical storms. Precipitation along the Texas coast is highly variable and linked to ENSO (Tolan, 2007; Pollack et al. 2011). From October to March, ENSO produces increased precipitation over the southwest United States. During El Niño events, a low-pressure system develops over the Texas coast and forms consistent thunderstorms, and the amount of freshwater introduced to the estuaries increases. During La Niña events this low-pressure system shifts up, over the mid-latitude regions of the United States causing a decrease in precipitation over Texas estuaries (Kim et al. 2014).

Pollack et al. (2011) examined a 20-year (1988-2009) data set from the Lavaca-Colorado Estuary, which demonstrated benthic community abundance, biomass, and diversity are in decline. The study attributed this decline to changes in salinity caused by El Niño and La Niña events. During the first half of the study, more El Niño effects were evident, and as a result, changes in salinities in the estuary were correlated with river discharge and ONI (Ocean Niño Index). Benthic abundance was correlated with changes in salinity, and ONI indicating that changes in climate influence benthic communities. NAO (North Atlantic Oscillation) and NPI (North Pacific Index) climate indices were analyzed in this 20-year study, but correlations between these two indices and benthic abundance, biomass, and diversity in the Lavaca-Colorado Estuary were not significant.

The purpose of the current study is to determine if the findings of Pollack et al. (2011) are localized or regional by comparing the benthic trends in the Lavaca-Colorado Estuary to benthic trends in the Guadalupe and Nueces Estuaries. Infaunal benthic invertebrates were used as a bioindicator of changes in estuary condition because they are abundant, diverse, sessile, long-lived, provide a response to multiple stressors (Montagna et al. 2010), and form the basis of the estuary food chain (Tunnell et al. 1996). Benthic community metrics such as abundance, biomass, and diversity show how the benthic community changed over time due to changes in water quality. Because benthic invertebrates form the basis of the estuary food chain, Texas Parks and Wildlife monthly trawl data of epifauna was analyzed with the infauna community metrics to determine if trends in both benthic communities are influenced by climate, or if there is an inverse trend of infauna and epifauna as would be expected if epifauna were preying on infauna. The long-term dataset for the Lavaca-Colorado, Guadalupe and the Nueces Estuary ranges over 23 years from 1986-2009.

METHODS

Study Area

Texas Estuaries

Texas has seven major and five minor estuaries along its coast. Texas estuaries lie along a climatic gradient. This climatic gradient influences the amount of freshwater the estuaries receive based on location. Precipitation decreases from Northeast to Southwest along the Texas coast. Texas estuaries range from nearly fresh water estuaries such as Sabine Lake, to hypersaline estuaries such as the Laguna Madre. Most bays are fed by one or two rivers draining watersheds. The rivers generally flow into the secondary bay and primary bays have a greater marine influence from the Gulf of Mexico (Montagna et al. 2007; Tolan, 2007). The quality, quantity, and timing of fresh water inflow from rivers is important to maintaining each estuary's natural salinity gradient, nutrient, and sediment loading regimes. These characteristics are important to maintaining estuary function and integrity (Palmer et al. 2011). The estuaries investigated in this study, moving from Northeast to Southwest, are Lavaca-Colorado Estuary, Guadalupe Estuary, and Nueces Estuary (Figure 1).

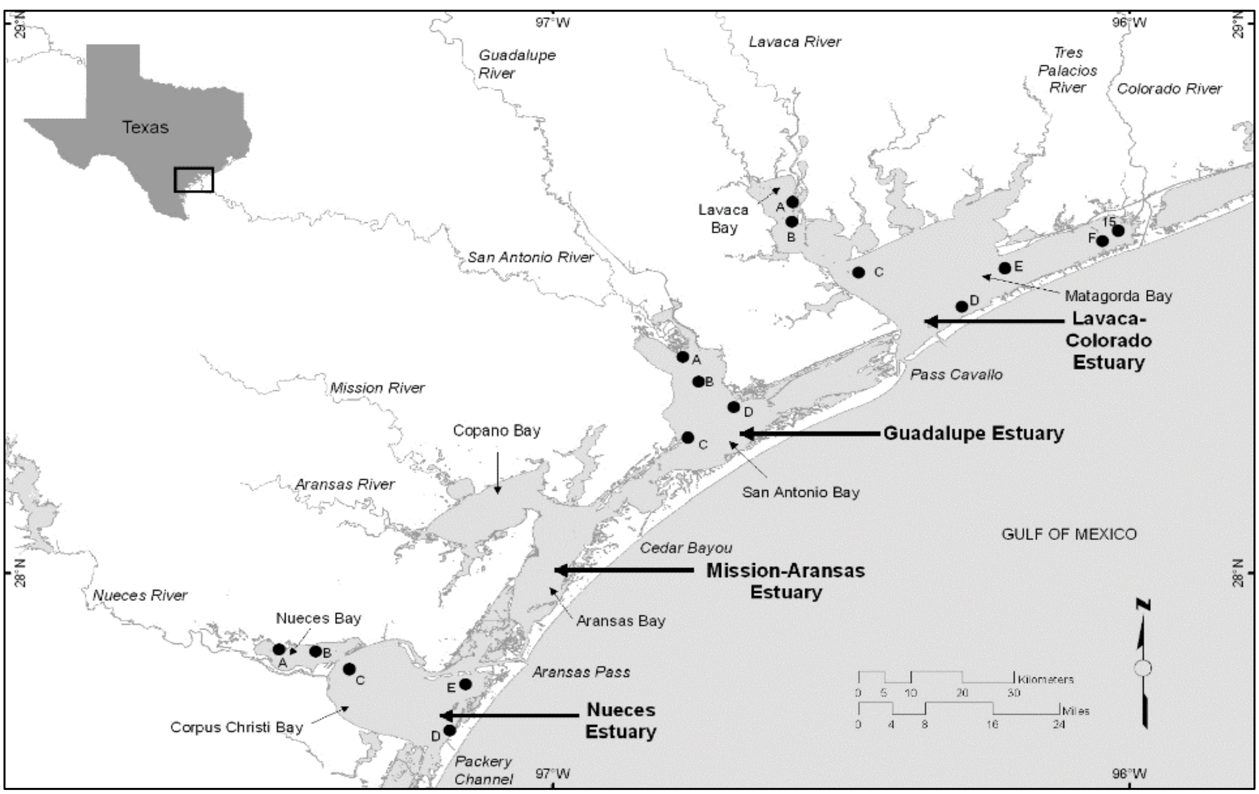

Figure 1 Study stations: All study stations for the Lavaca-Colorado, Guadalupe, and Nueces Estuary. Station 15 in the Lavaca-Colorado Estuary and Mission Aransas Estuary are not included in this study.

Lavaca-Colorado Estuary

The Lavaca-Colorado Estuary is an embayment estuary made up of primary bay Matagorda Bay, secondary bay Lavaca Bay, and smaller tertiary bays such as Tres Palacios Bay (Britton & Morton, 1989) (Figure 1). The estuary covers over 1200 km^2 and receives 107 cm of rainfall per year. The Lavaca-Colorado estuary receives freshwater inputs from the Colorado River, Lavaca River, and the Tres Palacios River (Pollack et al. 2011). The Lavaca River delivers freshwater inflow to Lavaca Bay, and the Colorado River delivers freshwater to Matagorda Bay. Due to anthropogenic changes, such as the installation of reservoirs, diversions, waste water and irrigation return flows, some segments of the Colorado River do not exhibit natural flow regimes.

Precipitation patterns over the Lavaca-Colorado Estuary can cause periods of low river flows and periods of high river flows. Low river flows restrict the amount of aquatic habitat, increase the amount of organic material deposited, elevate water temperature and maintain adequate levels of dissolved oxygen. High river flows maintain the channel substrate characteristics, serve as recruitment periods for organisms, and restore channel water quality after an extended period of low flows (Colorado and Lavaca Rivers and Matagorda and Lavaca Bays Basin and Bay Expert Science Team, 2011).

Guadalupe Estuary

The Guadalupe Estuary contains San Antonio Bay, Mesquite Bay and Espiritu Santo Bay (Figure 1). The total area of the estuary is 578 km^2. The estuary's primary bay (San Antonio Bay) connects to the Gulf of Mexico. The estuary's secondary bays (Mesquite Bay and Espiritu Santo Bay) empty into the primary bay and are removed from access to the Gulf of Mexico. The tides in the Guadalupe Estuary range from 0.15 meters in the bays to 0.6 meters along the Gulf of Mexico shoreline.

Peak influx of freshwater inflow to the estuary happens in the spring. Fresh water from the San Antonio and Guadalupe Rivers floods marsh areas, reduces bay salinities, and delivers nutrients and sediments from the estuary to the Gulf of Mexico. During times of decreased fresh water inflow, stream velocity decreases and sediment settles forming bay head deltas at the mouths of the San Antonio and Guadalupe Rivers. Marsh areas in the estuary are associated with these deltas (Texas Department of Water Resources 1981).

Nueces Estuary

Open bay, scattered seagrass meadows and oyster reefs are the habitat types that make up the Nueces Estuary. The estuary has a total surface area of 444.51 km^2, and an average depth of 2.4 m. The Nueces Estuary includes primary bay Corpus Christi Bay, and two secondary bays Oso Bay and Nueces Bay (Figure 1). Corpus Christi Bay gets tidal exchange from the Gulf of Mexico via Aransas Pass and Packery Channel. The average salinity of the Nueces Estuary is 27. In the winter, the difference in average salinity between Nueces Bay and Corpus Christi Bay can be 5, in the summer this difference can be as much as 15 (Tunnell et al.1996).

Freshwater inflow into the Nueces Estuary and access to the Gulf of Mexico affects salinity levels in the estuary. Mean freshwater inflow into the Nueces Estuary is 64,193,030.02 m^3/month (from 1941-1987). The amount of freshwater inflow the estuary receives varies seasonally. Anthropogenic development has altered the flow of the Nueces River to the Nueces Estuary. The City of Corpus Christi and San Patricio County Municipal Water District get their water from the Nueces River via the Choke Canyon Reservoir and Lake Corpus Christi (Nueces River, Corpus Christi, and Baffin Bay Expert Science Team, 2011).

Sampling Design

From 1986- 2009, 6 stations in the Lavaca-Colorado Estuary (labeled A-F), 4 stations in the Guadalupe Estuary (labeled A-D), and 5 stations in the Nueces Estuary (labeled A-E) were sampled quarterly (January, April, July, and October) for benthic abundance and diversity as well as water quality (Figure 1). The stations were lined up in a transect across the estuary based on the estuary's salinity gradient. Stations A and B for each estuary were in the secondary bays closest to the river. Station F for the Lavaca-Colorado Estuary, Station D for the Guadalupe Estuary, and Station E for the Nueces Estuary were in the primary bay and had the closest proximity to the Gulf of Mexico.

The bays of interest in this study are Lavaca Bay and Matagorda Bay (Lavaca-Colorado Estuary), San Antonio Bay (Guadalupe Estuary), and Nueces Bay and Corpus Christi Bay (Nueces Estuary). In this study, San Antonio Bay is divided into two bay systems known as Upper San Antonio Bay and Lower San Antonio Bay. Upper San Antonio Bay encompasses stations A and B and Lower San Antonio Bay encompasses stations D and E (Figure 1).

<u>Sampling Methods</u>

The field sampling methods used for this study are the same as the methods published in Pollack et al. (2011) long term Lavaca-Colorado study. During quarterly sampling events 3 benthic cores were collected at each station.-Hydrographic measurements (dissolved oxygen, salinity, water temperature, and nutrients), wind speed and direction, cloud cover, and wave height were recorded in conjunction with the benthic cores.

Benthic infauna was sampled using a 6.7 cm diameter core to a depth of 10 cm. Each replicate core collected was preserved with 5% buffered formalin with Rose Bengal. Hydrographic measurements were taken using a YSI sonde and were measured at the top 1 meter and the bottom of the bay.

In the laboratory, benthic infauna was extracted from the sediment using 500 µm mesh sieves, sorted using stereoscopes to the lowest practical identifiable level (usually species), and counted. Dry weight biomass measurements were recorded after the benthic infauna had been combined by taxonomic order (Crustacea, Polychaeta, and Mollusca and others) and dried in a 50^{o}C drying oven for 24 hours then weighed. Mollusk shells were removed with 1 N HCl prior to drying and weighing.

Statistical Methods

Quarterly average benthic infauna abundance, biomass, and diversity was calculated by bay over the entire study period. Infauna diversity was calculated using Hill's N1 Diversity index on pooled replicates (106 cm^2). Quarterly average salinity, dissolved oxygen (DO), and pH was calculated over the entire study period. Sediment cores were analyzed for average grain size over the study period. This data was used to characterize each estuary. Tables were created to visualize the data using SAS 9.4 software.

Macrobenthic infauna community structure within the bays was analyzed using non-metric multidimensional scaling (nMDS) on square root transformed data. The differences and similarities in macroinfauna community structure in the bays were highlighted using a cluster analysis, and an nMDS plot was created to visualize these data using PRIMER7 software.

Monthly hydrologic and monthly trawl data for each estuary was obtained from Texas Parks and Wildlife Department (TPWD) for analysis of long-term trends in estuary hydrology and epifauna abundance. TPWD has study stations that cover the bays of Texas. Each month TPWD randomly samples at these sights. For this analysis a pseudo-fixed sampling data set was created by sorting TPWD sampling stations by bay. Stations from bays that were not near the infauna stations were omitted. The data was then analyzed overtime using a regression, and spearman correlations determined the relationship between benthic community metrics, hydrologic parameters, and predator abundance. TPWD data collected throughout the estuaries is associated with their fisheries -independent monitoring program.

Monthly inflow data was obtained from the Texas Water Development Board was used to analyze long-term trends in freshwater inflow. Total surface inflow from the river basin was estimated by summing the flows in both gauged and ungauged watersheds. The gauges are property of the United States Geological Survey (USGS) and are used for their streamflow records. Ungauged flows are the sum of computed river flow (calculated based on the TWDB's rainfall-runoff simulation model (TXRR)), diverted river flow (for municipal, agricultural and other uses), and unconsumed river flow returned to the rivers (TWDB 2017).

Average salinity, dissolved oxygen, pH was calculated and used to analyze the relationship between these long-term hydrologic variables and average benthic abundance, biomass and diversity over the entire study period. Sediment cores collected at the time of benthic sampling were used to characterize each estuary. Percentage of sand, silt, clay and rubble were averaged over the entire study period.

To analyze the role of climate variability on Texas estuaries, monthly Ocean Niño Index (ONI) was used to evaluate ENSO conditions. ONI data was obtained from NOAA Climate Prediction Center (CPC). The ONI consists of 3-month average sea surface temperature (SST) anomalies recorded in the Niño 3.4 region. The CPC, defines El Niño (warm) and La Niña (cool) episodes based on a threshold of +/-0.5 °C for the ONI. El Niño occurs when the ONI is above 0.5°C and La Niña occurs when the ONI is less than -0.5°C for five consecutive months. Months where the ONI was in between -0.5 and 0.5°Care months that are not indicative of an El Niño or La Niña event and are considered neutral months. (NOAA Climate Prediction Center, 2001).

Regression over the time series for both infauna and epifauna were analyzed on both raw and log transformed (log10 (n + 1)) data.

RESULTS

Physical Conditions

Water temperature slightly increased over the course of the study within each estuary and showed a strong seasonal signal. Warmer temperatures occurred in summer months and cooler temperatures occurred in winter months (Figure 2). Average temperature of each bay over the course of the study, was similar ranging from 22 ^{o}C in Lavaca Bay to 23 ^{o}C in Nueces Bay (Table 1)

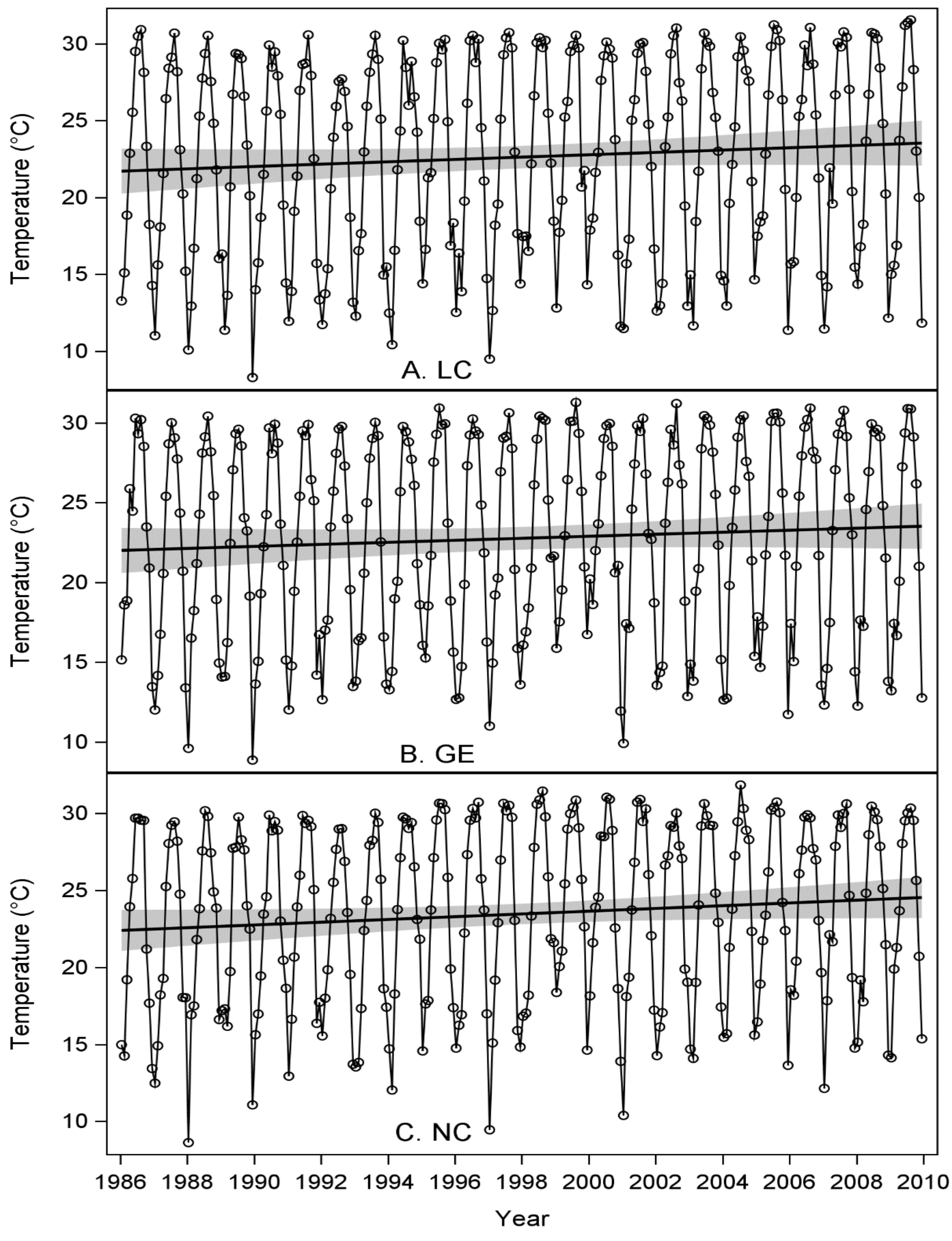

Figure 2 Average monthly temperature within estuaries. Each point represents average monthly temperature estuary wide, and the line is a linear regression over time (with 95% confidence limits). A. Lavaca-Colorado (LC). B. Guadalupe (GE). C. Nueces (NC).

In each estuary, dissolved oxygen significantly decreased over time (Lavaca Colorado $r = -0.20870$ $p = 0.0004$, Guadalupe Estuary $r = -0.18336$ $p = 0.0018$, Nueces Estuary $r = -0.22763$ $p < 0.0001$). Dissolved oxygen showed a strong seasonal signal with a maximum concentration in the winter and a minimum concentration in the summer for each estuary (Figure 3). Average dissolved oxygen concentration over the study period was similar for each bay.-Corpus Christi Bay had the lowest average dissolved oxygen concentration 6.85 mg l^{-1} and Upper San Antonio Bay had the highest average dissolved oxygen concentration 8.48 mg l^{-1} Overall dissolved oxygen concentrations were higher in the secondary bay than the primary bay. (Table 1).

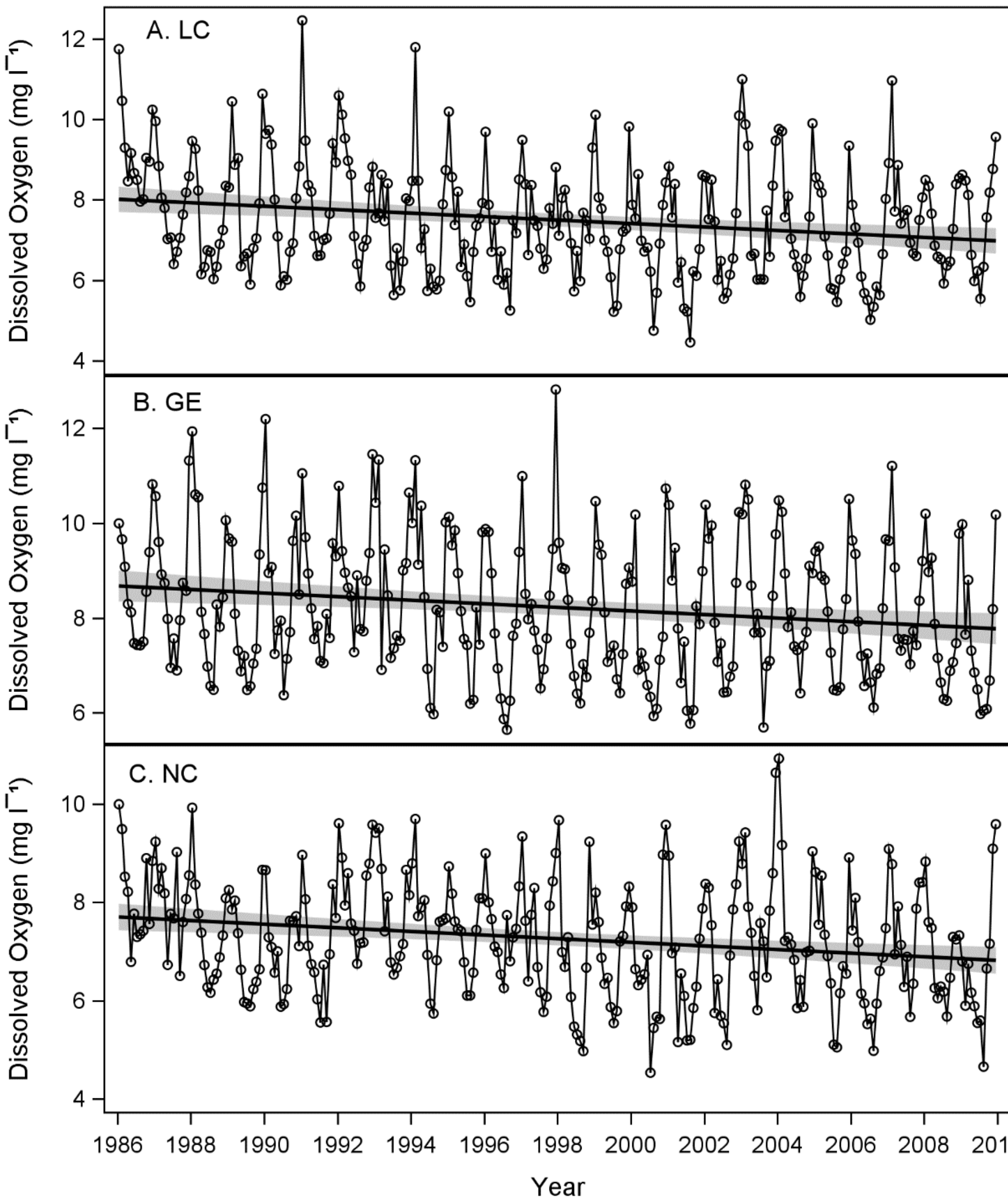

Figure 3 Average monthly dissolved oxygen concentrations within estuaries. Each point represents a monthly average dissolved oxygen (DO) estuary-wide, and the line is a linear regression over time (with 95% confidence limits). A. Lavaca-Colorado (LC). B. Guadalupe (GE). C. Nueces (NC).

Sediment composition was similar within each estuary. Each estuary was made up of a mixture of rubble, sand, silt and clay. Each of the bays investigated in this study had low concentrations of rubble, high concentrations of clay in the Lavaca-Colorado estuary, high concentrations of sand in Lower San Antonio Bay, and high concentrations of silt in Upper San Antonio Bay and the Nueces Estuary (Table 1).

Table 1. Averages for all macroinfauna, hydrographic, and sediment variables sampled quarterly in each estuary from 1986-2009.Matagorda Bay, Lower San Antonio Bay, and Corpus Christi Bay are the primary bays. Lavaca Bay, Upper San Antonio, and Nueces Bay are the secondary Bays.

	Estuary and Bay					
	Lavaca		**Guadalupe**		**Nueces**	
Variable	**Lavaca**	**Mata-gorda**	**Lower San Antonio**	**Upper San Antonio**	**Corpus Christi**	**Nueces**
Abundance (n m^{-2})	6079	11460	9714	21168	16723	11271
Biomass (g m^{-2})	1.24	5.19	4.09	14.02	9.61	6.87
Diversity (N1 106 cm^{-2})	3.74	10.56	5.11	3.86	17.37	9.64
Dissolved Oxygen (mg l^{-1})	7.93	7.57	8.16	8.48	6.85	7.45
Salinity	16.29	23.91	17.69	10.24	31.56	26.2
Temperature (ºC)	21.74	22.33	22.37	22.49	22.46	22.7
pH	8.11	8.14	8.22	8.28	8.10	8.13
NH4 (µmol l^{-1})	2.97	2.22	1.82	3.02	1.52	2.37
PO4 (µmol l^{-1})	2.13	1.20	1.98	3.43	0.63	1.80
SiO4 (µmol l^{-1})	105.33	58.30	108.73	150.30	51.23	112.50
NOx (µmol l^{-1})	4.83	2.95	5.70	25.67	0.85	2.41
Clay (%)	37.19	43.68	22.38	31.25	29.44	22.83
Rubble (%)	1.63	2.31	4.36	9.20	6.88	9.72
Sand (%)	35.16	22.85	51.46	22.24	47.82	51.30
Silt (%)	26.02	30.99	21.80	38.35	19.71	19.04

ONI values fluctuated from positive to negative with 2 to 4-year periodicity. According to the CPC's definition, there were 9 El Niño events and 8 La Niña events during the study period. Each El Niño and La Niña event varied based on duration and intensity (Figure 4).

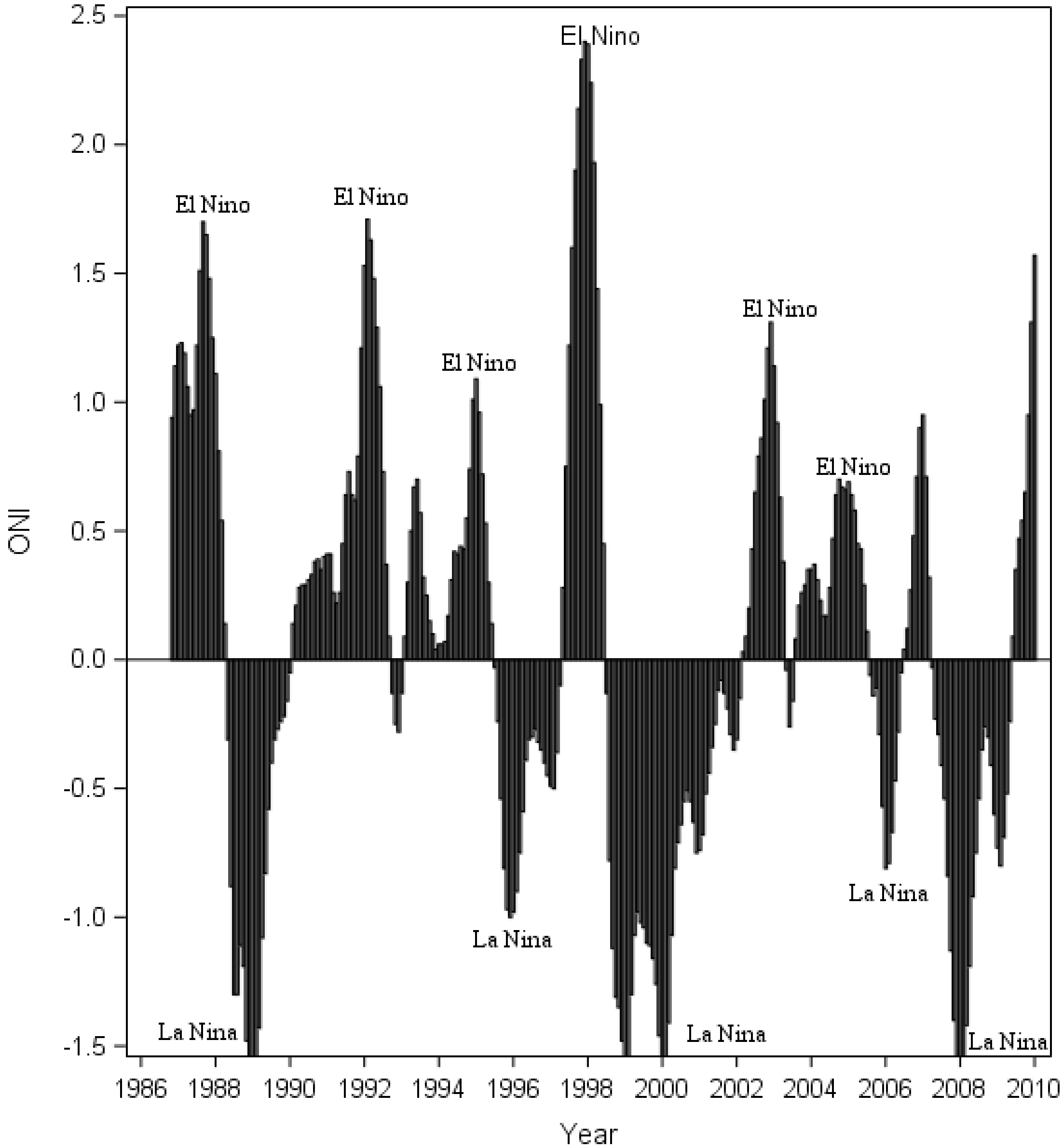

Figure 4. Monthly Ocean Niño index (ONI) Values. ONI values above 0.5 ºC are indicative of El Niño events and ONI below -0.5 ºC for 5 months are indicative of La Niña Events.

Inflow into the Lavaca-Colorado Estuary ranged from 10,194,712 to 4,789,744,690 m^3/month, while the Guadalupe Estuary ranged from 9,124,052 to 3,057,092,602 m^3/month, and Nueces Estuary ranged from -5,698,678 to 1,162,442,653 m^3/ month (Figure 5). Across all three estuaries, the ONI was positively correlated with inflow and DO, and negatively correlated with salinity (Table 2).

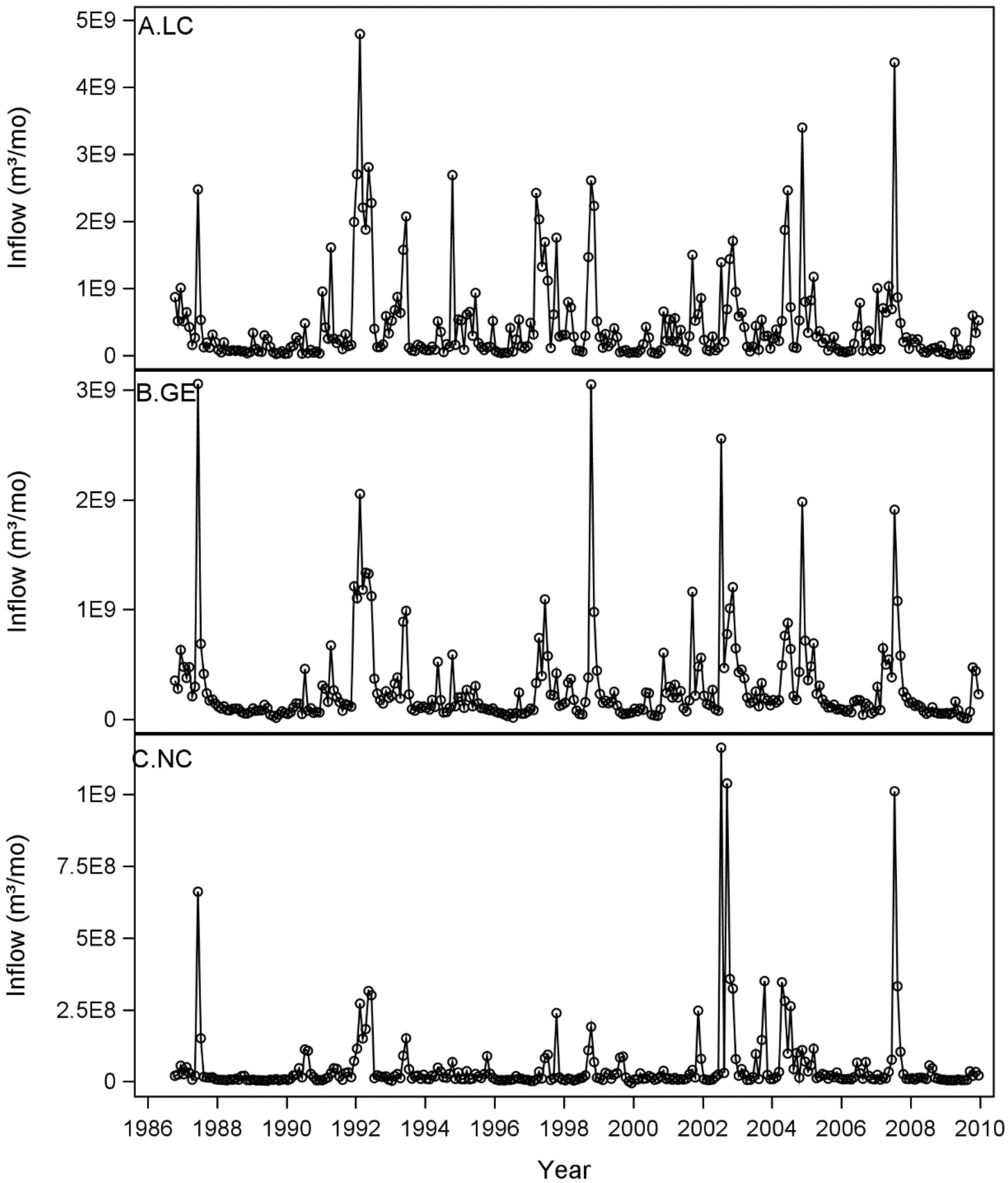

Figure 5. Average monthly gauged inflow within estuaries. Each point represents a monthly average inflow estuary-wide. A. Lavaca-Colorado (LC). B. Guadalupe (GE). C. Nueces (NC).

Table 2. Spearman correlation relating Salinity, Dissolved Oxygen, Temperature and Inflow to climate indices within the Lavaca-Colorado Estuary (LC), Guadalupe Estuary (GE), and Nueces Estuary (NC).

Climate Index	Stat	Salinity (psu)			Temperature (°C)		
		LC	GE	NC	LC	GE	NC
ONI	r	0.461	0.396	0.330	0.030	0.046	0.052
	p	<0.0001	<0.0001	<0.0001	0.6161	0.4449	0.3863

Climate Index	Stat	Inflow (m^3/month)			Dissolved Oxygen (mg l^{-1})		
		LC	GE	NC	LC	GE	NC
ONI	r	0.385	0.419	0.311	0.119	0.134	0.186
	p	<0.0001	<0.0001	<0.0001	0.0468	0.0248	0.0018

Similarities between benthic infauna communities

A total of 413 species were recorded in the Lavaca-Colorado, Guadalupe, and Nueces estuaries from 1986-2009. The macrofauna assemblage was dominated by polychaetes with *Mediomastus ambiseta* being the most abundant species representing 35% of all individuals found over the 22-year study period. The 15 most abundant organisms comprised 10 annelids (oligochaetes & polychaetes included in this count), 2 mollusks, 2 crustaceans and 1 nemertean. The nemertean and oligochaetes were not identified to more specific taxa groupings. These fifteen organisms accounted for more than 80% of the data (Table 3).

Table 3 Average infauna species abundance (n m-2) measured in each bay over all samples collected from 1986-2009. Abbreviations: SpName= taxa name of lowest practical identifiable level, Cum%= cumulative percent.

Rank	SpName	Lavaca Bay	Matagorda Bay	Upper San Antonio Bay	Lower San Antonio Bay	Corpus Christi Bay	Nueces Bay	Mean	%	Cum%
1	*Mediomastus ambiseta*	3582	4367	6956	5146	3643	3733	4571	35.30	35.30
2	*Streblospio benedicti*	931	395	5976	1084	666	1420	1745	13.48	48.77
3	*Mulinia lateralis*	337	344	1886	704	125	1136	755	5.83	54.61
4	*Texadina sphinctostoma*	11	0	3975	359	0	0	724	5.59	60.20
5	*Dipolydora caulleryi*	0	981	0	174	2600	567	720	5.56	65.76
6	*Tharyx setigera*	1	152	0	11	1799	477	407	3.14	68.90
7	*Apseudes sp. A*	0	1524	0	0	0	0	254	1.96	70.86
8	Oligochaeta (unidentified)	16	508	289	16	543	13	231	1.78	72.64
9	Nemertea (unidentified)	91	332	204	188	345	129	215	1.66	74.30
10	*Cossura delta*	170	499	0	50	254	98	178	1.38	75.68
11	*Ampelisca abdita*	200	56	370	18	26	217	148	1.14	76.82
12	*Clymenella torquata*	1	22	1	23	299	467	136	1.05	77.87
13	*Gyptis brevipalpa*	12	197	7	26	336	227	134	1.03	78.90
14	*Paleanotus heteroseta*	0	51	0	1	699	18	128	0.99	79.89
15	*Glycinde solitaria*	65	103	34	125	149	98	95	0.74	80.63
	398 other species	662	3396	1503	1787	4956	2749	2509	19.37	100.00
	Total	6078	12926	21199	9712	16439	11350	12951	100.00	

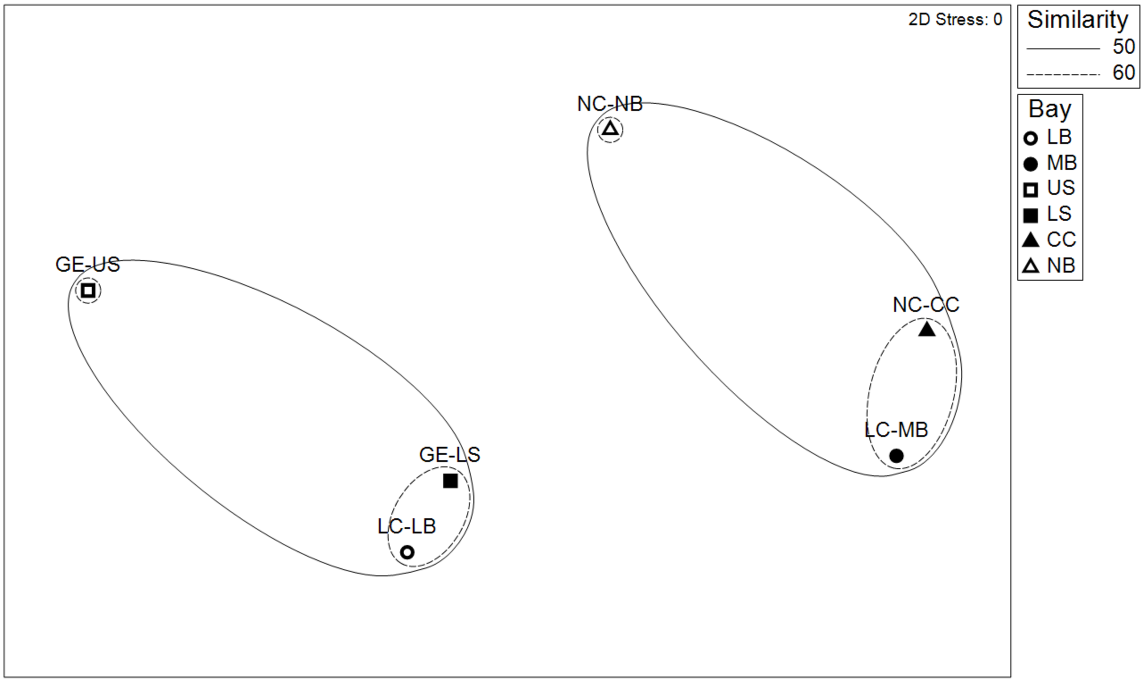

Figure 6. nMDS Plot of community structure by bay. Each symbol on the nMDS is representative of estuary. Triangles pointed up are Lavaca-Colorado (LC) estuary samples, Lavaca bay (LC-LB) Matagorda bay (LC-MB). Triangles pointed down are Guadalupe Estuary (GE) samples, Upper San Antonio Bay (GE-US), Lower San Antonio Bay (GE-LS). Squares are Nueces (NC) Estuary samples Nueces Bay (NC-NB) Corpus Christi Bay (NC-CC).

Benthic macrofauna community structure and average species abundance, over the 22-year study was analyzed by bay using an nMDS plot. Overall, the communities clustered into 4 different-groups. Upper San Antonio Bay, Lower San Antonio Bay, and Lavaca Bay shared 50% similarity in community structure and abundance. Nueces Bay, Corpus Christi Bay, and Matagorda Bay had 50% similarity in community structure and abundance. Lower San Antonio Bay and Lavaca Bay shared 60% similarity and Corpus Christi Bay and Matagorda Bay had 60% similarity in community structure and abundance (Figure 6).

Correlations between estuary conditions (salinity, DO, and temperature), and benthic metrics (abundance and biomass) varied by estuary. In the Lavaca-Colorado estuary and Guadalupe Estuary benthic community biomass and diversity were positively correlated with salinity. Benthic community abundance in the Lavaca-Colorado Estuary was also positively correlated with salinity. In the Guadalupe Estuary benthic abundance and biomass were positively correlated with DO. Benthic diversity in the Lavaca-Colorado Estuary and abundance in the Guadalupe Estuary were negatively correlated with temperature. Benthic abundance, biomass, and diversity were not correlated with salinity, DO, or temperature in the Nueces Estuary (Table 3).

Table 4 Spearman correlations showing the relationship between benthic abundance, biomass, and diversity and salinity, DO, and temperature by Estuary from 1986-2009.

Variable	**Stat**	**Lavaca-Colorado**			**Guadalupe**			**Nueces**		
		Abundance n m^{-2}	**Biomass g m^{-2}**	**Divversity N1**	**Abundance n m^{-2}**	**Biomass g m^{-2}**	**Divversity N1**	**Abundance n m^{-2}**	**Biomass g m^{-2}**	**Divversity N1**
Salinity	r	0.43	0.52	0.42	0.11	0.52	0.52	0.29	0.31	0.19
	p	0.04	0.01	0.05	0.63	0.02	0.02	0.19	0.16	0.39
DO	r	0.03	0.16	0.36	0.48	-0.45	-0.23	-0.18	-0.32	-0.39
	p	0.88	0.49	0.09	0.03	0.05	0.13	0.42	0.15	0.07
Temperature	r	-0.29	-0.36	-0.59	-0.60	0.33	0.35	-0.11	0.27	0.36
	p	0.18	0.1001	0.004	.0049	0.15	0.13	0.63	0.22	0.09

There were declining trends in benthic abundance across all three estuaries over the 22-year study period. In the Lavaca-Colorado Estuary and the Nueces Estuary, benthic abundance was higher in the primary bay than the secondary bay. In the Guadalupe Estuary, benthic abundance was higher in the secondary bay (Figure 7).

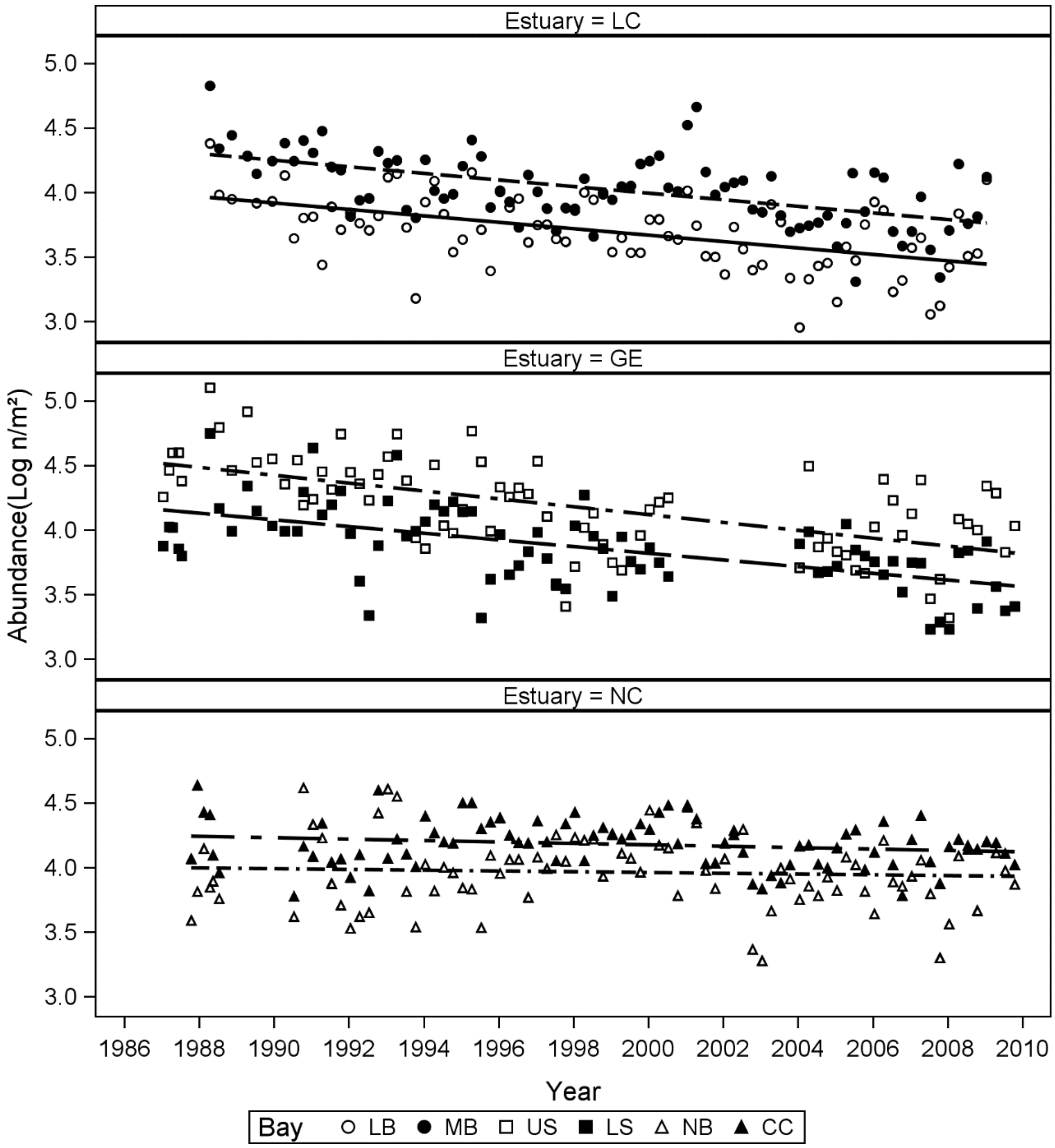

Figure 7. Average quarterly (January, April, July October) benthic infauna abundance by bay from January 1986-October 2009. The Lavaca-Colorado Estuary (LC) is made up of Lavaca Bay (LB, open circles) and Matagorda Bay (MB, closed circles). The Guadalupe Estuary (GE) is made up of Upper San Antonio Bay (US, open squares) and Lower San Antonio Bay (LS filled squares). The Nueces Estuary (NC) is made up of Nueces Bay (NB, open traiangles) and Corpus Christi Bay (CC, filled triangles).

Benthic infauna biomass declined in the Nueces Estuary and the Lavaca-Colorado estuary. Biomass was higher in the primary bays for these two estuaries. In the Guadalupe Estuary, biomass increased in the primary bay and decreased in the secondary bay (Figure 8).

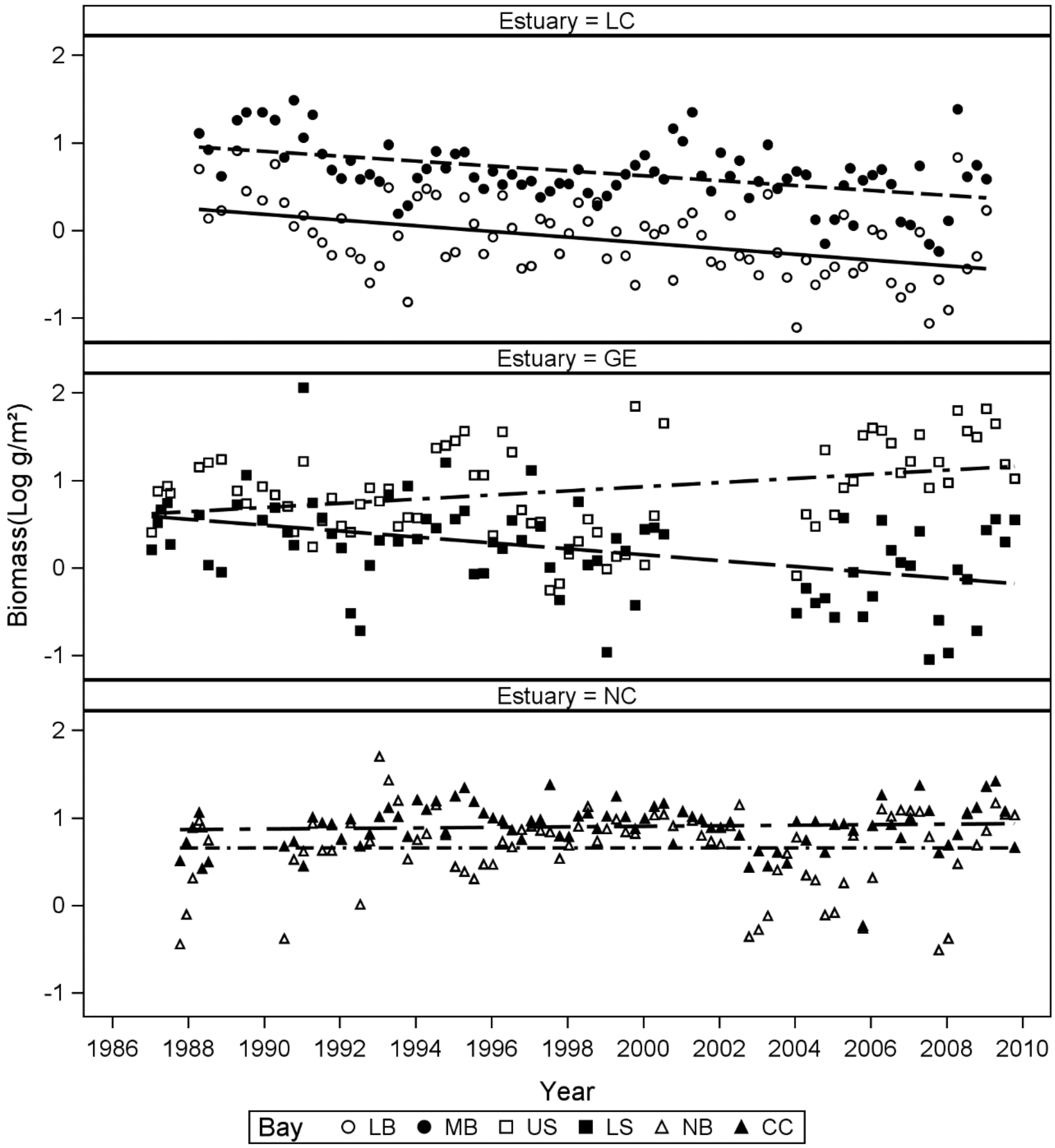

Figure 8. Average quarterly (January, April, July October) benthic infauna biomass by bay from January 1986- October 2009. The Lavaca-Colorado Estuary (LC) is made up of Lavaca Bay (LB, open circles) and Matagorda Bay (MB, filled circles). The Guadalupe Estuary (GE) is made up of Upper San Antonio Bay (US, open square) and Lower San Antonio Bay (LS, filled square). The Nueces Estuary (NC) is made up of Nueces Bay (NB, open triangle) and Corpus Christi Bay (CC, filled triangles).

Infauna diversity in the Lavaca-Colorado Estuary and Guadalupe Estuary declined over the 22-year study period and increased in the Nueces Estuary. Primary bays had higher diversity than secondary bays (Figure 9).

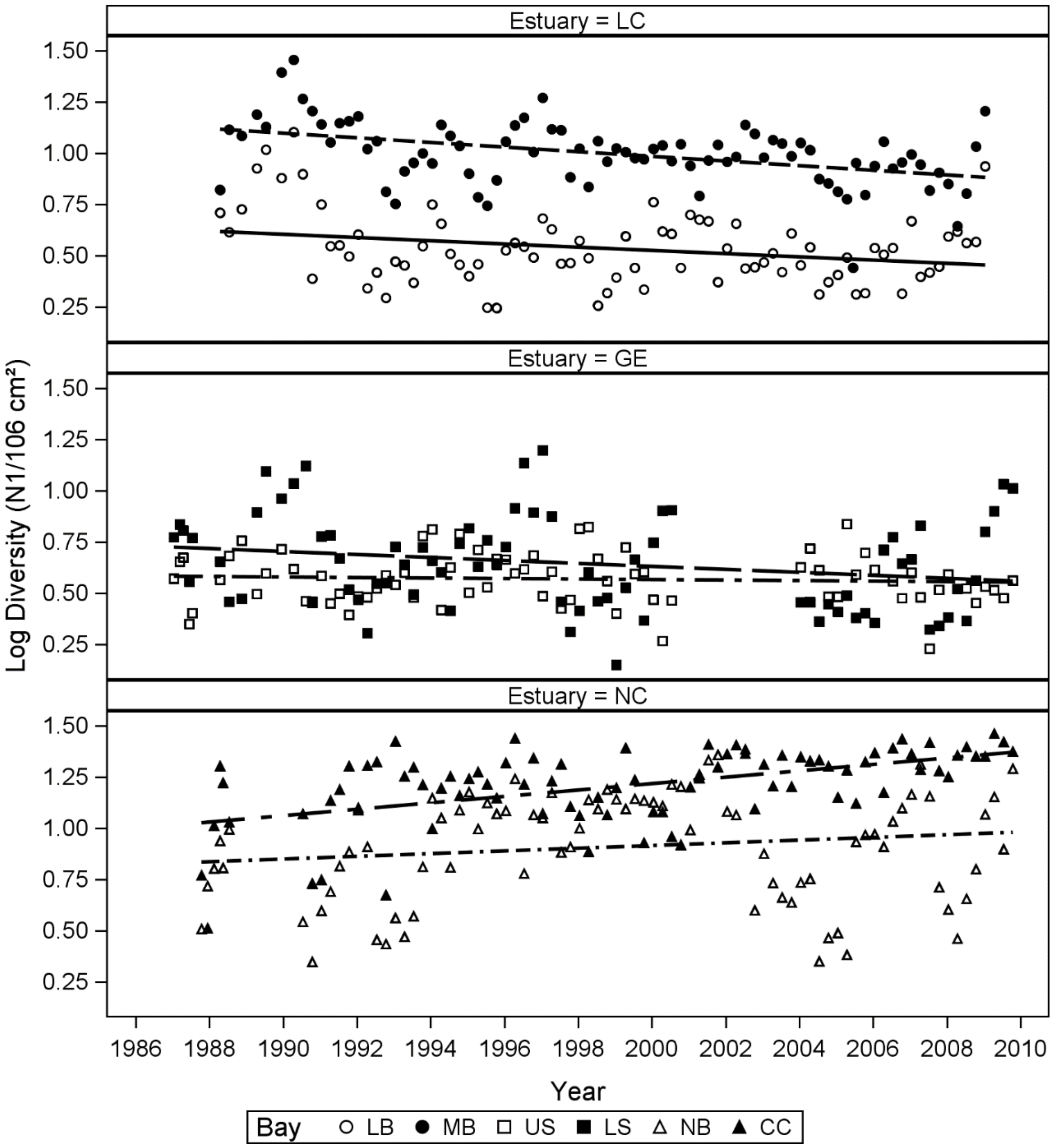

Figure 9. Average quarterly (January, April, July October) benthic infauna diversity by bay from January 1986- October 2009. . The Lavaca-Colorado Estuary (LC) is made up of Lavaca Bay (LB, open circles) and Matagorda Bay (MB, filled circles). The Guadalupe Estuary (GE) is made up of Upper San Antonio Bay (US, open square) and Lower San Antonio Bay (LS, filled square). The Nueces Estuary (NC) is made up of Nueces Bay (NB, open triangle) and Corpus Christi Bay (CC, filled triangles).

Epifauna Populations

Over the 22-year study period, the total number of epifauna sampled per month by Texas Parks and Wildlife varied by bay. Epifuana abundance, species richness, and diversity across all the estuaries studied had increasing trends. (Figure 10, Figure 11, Table 5). Corpus Christi Bay had the highest total number of epifauna sampled over the study period 916,969, and Nueces Bay had the lowest total number of epifauna sampled 56,264 (Table 5). Over the course of the study, epifaunal abundance, richness and diversity trends were positively correlated with temperature trends and inversely correlated with DO trends. Correlations between salinity and epifaunal abundance and species richness varied by bay. More epifauna were sampled in the primary bays than secondary bays (Figure 10 and Table 5).

Table 5 Linear regression equations for epifaunal abundance by estuary. Lavaca-Colorado (LC), Guadalupe Estuary (GE), Nueces Estuary (NC)

Epifauna Metric	Estuary	Regression equation	P-value
Abundance (1n (n+1)/trawl)	LC	Y=1.27-0.00003*mondate	<0.0001
	GE	Y=1.05-0.00006*mondate	<0.0001
	NC	Y=1.73-0.000012*mondate	<0.0001
Species Richness (species/trawl)	LC	Y=5.83-0.0002*mondate	<0.0001
	GE	Y=4.76-0.0002*mondate	<0.0001
	NC	Y=9.34+0.00004* mondate	<0.0001
Diversity (N1/Trawl)	LC	Y=3.97-0.00002*mondate	<0.0001
	GE	Y=3.99+0.0004*mondate	<0.0001
	NC	Y=4.56+0.00002* mondate	<0.0001

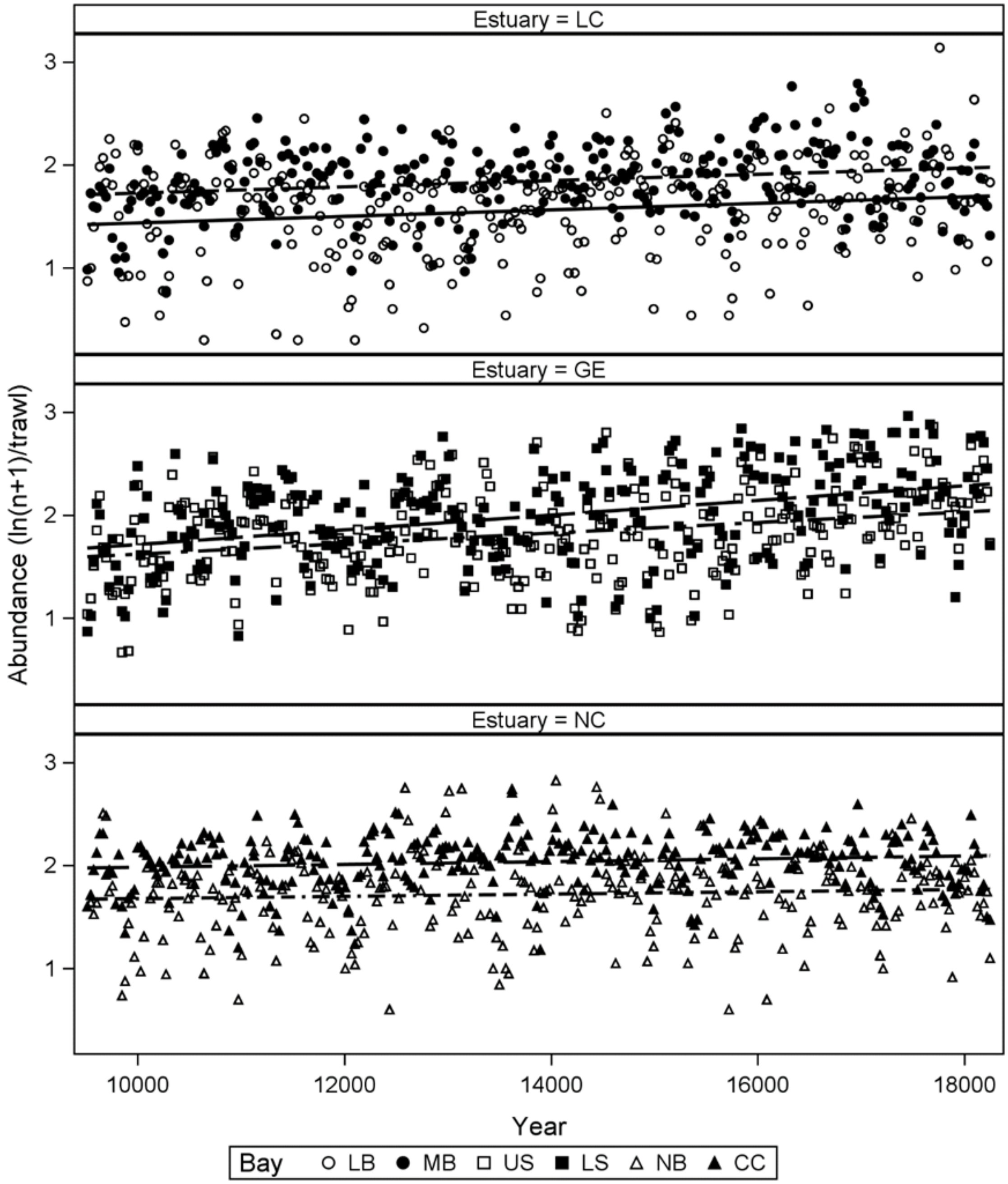

Figure 10. Total number of epifauna per month over the 22-year study in the bays Lavaca-Colorado estuary (LC) Lavaca Bay (LB), Matagorda Bay (MB), Guadalupe Estuary (GE), Upper San Antonio Bay (US), Lower San Antonio Bay (LS) and the Nueces Estuary (NC), Nueces Bay (NB), and Corpus Christi Bay (CC) 1987- 2009.

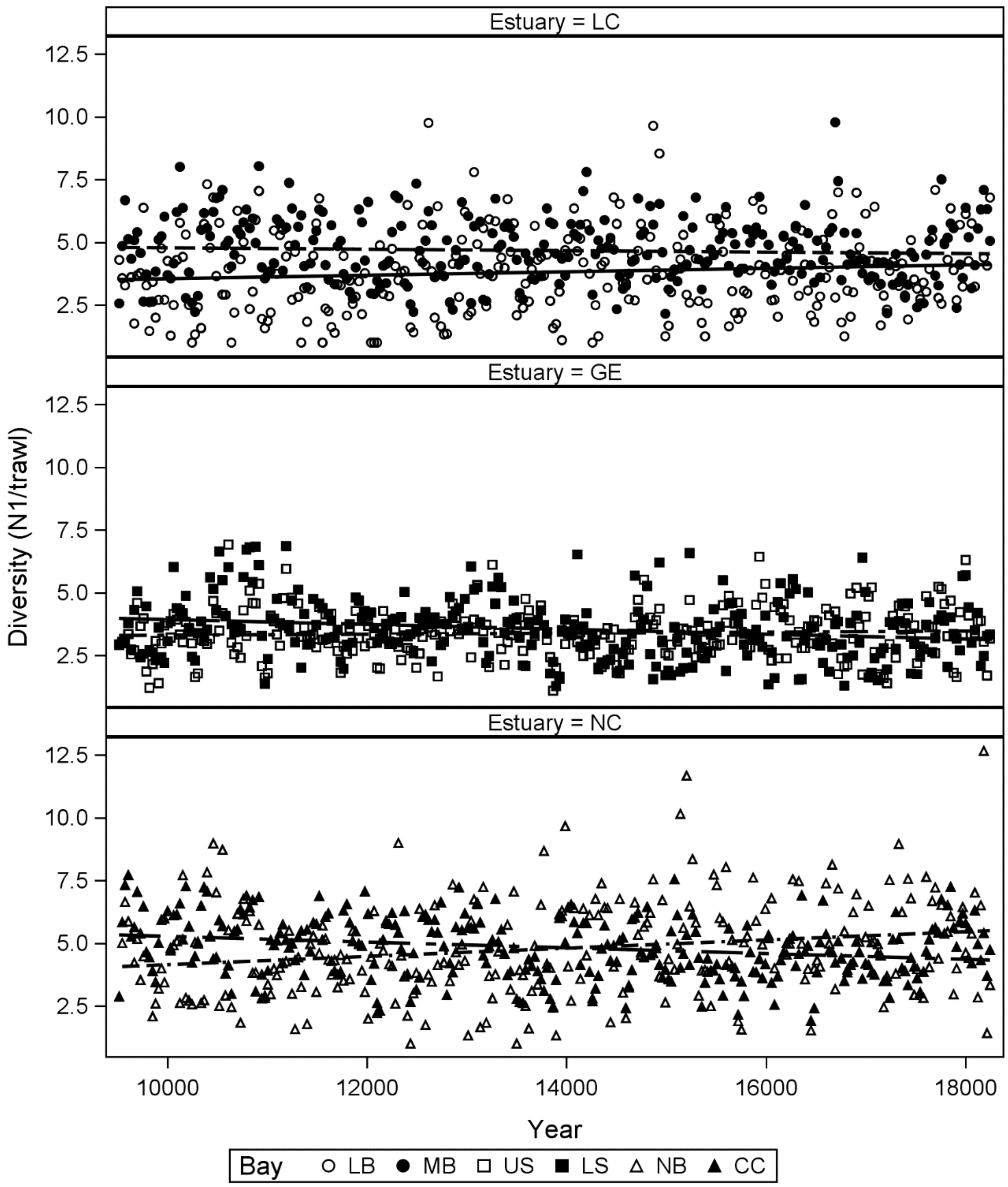

Figure 11 Epifauna diversity (N1/Trawl) per month over the 22-year study in the bays Lavaca-Colorado estuary (LC) Lavaca Bay (LB), Matagorda Bay (MB), Guadalupe Estuary (GE), Upper San Antonio Bay (US), Lower San Antonio Bay (LS) and the Nueces Estuary (NC), Nueces Bay.

Table 6. Total number of epifauna caught in trawls from January 1986- December 2009.

Variable	Estuary - Bay					
	Lavaca-Colorado		Guadalupe		Nueces	
	Lavaca	Matagorda	Upper San Antonio	Lower San Antonio	Nueces	Corpus Christi
A. Total number of Epifauna	68,248	619,287	292,437	640,857	56,264	916,969

Trends in benthic abundance did not correlate with trends in epifauna abundance in any of the estuaries studied (Table 7 A.). In Upper San Antonio Bay (US) benthic biomass was positively correlated with epifaunal abundance (number/trawl) and epifaunal species richness (species/ trawl) (Table 7 B.). Infaunal diversity was negatively correlated with epifauna diversity in Lavaca Bay (Table 7 C.). Infauna species richness was correlated with epifauna abundance in Matagorda and Lower San Antonio Bays (Table 7 D.).

Table 7. Statistics for epifauna and correlation of epifauna with infauna. Spearman correlation co-efficient relating (A.) log(10) transformed infaunal abundance (n/m^2), (B.) log(10) infaunal biomass (g/m2) , (C.) infaunal diversity (N1/106 cm2) and (D.) infaunal species richness (number

A.	Estuary	Bay	Statistic	Epifaunal Abundance	Epifaunal Richness	Epifaunal Diversity
Infaunal Abundance	LC	LB	r	-0.07	-0.09	-0.06
			p	0.50	0.44	0.61
		MB	r	-0.03	0.06	0.07
			p	0.77	0.61	0.50
	GE	US	r	-0.01	0.06	0.18
			p	0.89	0.57	0.11
		LS	r	-0.24	0.13	0.04
			p	0.03	0.24	0.73
	NC	NB	r	0.06	0.01	-0.11
			p	0.58	0.90	0.34
		CC	r	-0.04	-0.02	0.0007
			p	0.65	0.85	0.10

B.	Estuary	Bay	Statistic	Epifaunal Abundance	Epifaunal Richness	Epifaunal Diversity
Infaunal Biomass	LC	LB	r	0.04	0.003	-0.01
			p	0.70	0.97	0.94
		MB	r	0.06	0.08	0.04
			p	0.60	0.47	0.72
	GE	US	r	0.58	0.46	0.04
			p	<0.0001	<0.0001	0.72

		LS	r p	-0.14 0.22	-0.005 0.97	0.11 0.33
	NC	NB	r p	-0.01 0.91	0.09 0.41	0.03 0.82

		CC	r p	0.09 0.37	-0.01 0.92	0.04 0.70

C.	Estuary	Bay	Statistic	Epifaunal Abundance	Epifaunal Richness	Epifaunal Diversity
Infaunal Diversity	LC	LB	r p	-0.04 0.74	-0.14 0.22	-.22 0.05
		MB	r p	-0.19 0.08	-0.05 0.63	0.15 0.16
	GE	US	r p	0.07 0.52	-0.08 0.46	-0.14 0.21
		LS	r p	-0.17 0.15	0.09 0.43	0.21 0.07
	NC	NB	r p	0.08 0.50	0.19 0.10	0.08 0.47

D.	Estuary	Bay	Statistic	Epifaunal Abundance	Epifaunal Richness	Epifaunal Diversity
Infaunal Species Richness	LC	LB	r p	-.01 0.94	-0.06 0.58	-0.11 0.33
		MB	r p	-0.21 0.04	-0.11 0.29	0.02 0.81
	GE	US	r p	0.09 0.45	0.06 0.63	0.01 0.95
		LS	r p	-0.23 0.04	0.06 0.63	0.21 0.06
	NC	NB	r p	0.12 0.31	0.19 0.08	0.06 0.58
		CC	r p	0.10 0.38	-0.07 0.53	0.09 0.41

Table 8. Spearman correlations relating, DO, and temperature to average (A.) epifauna abundance (ln(n+1)/trawl), (B.) epifaunal diversity (N1/trawl), (C.) epifaunal species richness (species/trawl) by bay.

A.	Estuary	Bay	Statistic	Salinity	DO	Temperature
Epifaunal Abundance	LC	LB	r	01	-0.39969	0.50
			p	0.01	<.0001	<.0001
		MB	r	-0.08	-0.50	0.50
			p	0.20	<.0001	<.0001
	GE	US	r	0.27	-0.34	0.33
			p	<.0001	<.0001	<.0001
		LS	r	-0.04	-0.47	0.48
			p	0.55	<.0001	<.0001
	NC	NB	r	0.002	-0.36	0.47
			p	0.97	<.0001	<.0001
		CC	r	-0.07	-0.29	0.34967
			p	.21	<.0001	<.0001

B.	Estuary	Bay	Statistic	Salinty	DO	Temperature
Epifaunal Diversity	LC	LB	r	0.13	-0.39	0.43
			p	0.03	<.0001	<.0001
		MB	r	0.18	-0.33	0.32
			p	0.002	<.0001	<.0001
	GE	US	r	0.01	-0.32	0.29
			p	0.84	<.0001	<.0001
		LS	r	0.08	-0.21	0.25
			p	0.20	0.0003	<.0001
	NC	NB	r	0.02	-0.32626	0.39
			p	0.73	<.0001	<.0001
		CC	r	0.10	-0.07	0.09
			p	0.38	0.53	0.41

C.	Estuary	Bay	Statistic	Salinity	DO	Temperature
Infaunal Species Richness	LC	LB	r	0.21	-0.49	0.57
			p	0.0004	<.0001	<.0001
		MB	r	0.10	-0.52	0.49
			p	0.09	<.0001	<.0001
	GE	US	r	0.09	-0.50	0.48
			p	0.45	<.0001	<.0001
		LS	r	0.09	-0.32	0.30
			p	0.11	<.0001	<.0001
	NC	NB	r	0.07	-0.52	0.60
			p	0.27	<.0001	<.0001
		CC	r	0.06	-0.33	0.44
			p	0.32	<.0001	<.0001

DISCUSSION

According to the Domino Theory proposed by Albers (2002), inflow hydrology drives estuarine condition, and that drives biological response. However, this study (Table 2), and various other studies (Kim et al. 2014, Pollack et al. 2011; Tolan 2007) demonstrate that the Domino Theory is incomplete without referring to climate. Instead of starting with inflow, the theory should start with climate because climate drives the hydrologic cycle, and thus the amount of fresh water inflow delivered to the Texas coast (Tolan 2007, Pollack et al. 2011). Texas estuaries are a suitable location to study the effects of climate variation because they are physically similar, each estuary drains one or two watersheds, and they lie in a climatic gradient (Montagna et al. 2007) with decreasing precipitation from NE to SW (Tolan 2007). The local climatic gradient and ENSO have been influencing ecosystem hydrological (Tolan 2007) and ecological (Kim et al. 2014) dynamics in Texas estuaries.

Climate change is affecting precipitation patterns around the world, and this is having an impact on people, economies and ecosystems (Zimmerman et al. 2015). When 19 climate models (two of which are the National Center for Atmospheric Research's Community Climate System Model, and the Geophysical Fluid Dynamic Laboratory's Climate model), which participated in the Inter-governmental Panel of Climate Change (IPCC) Fourth Assessment Report, were analyzed, 18 of them predicted that climate will become more arid over time in the Southwestern United States (land between 125 °W and 95 °W and 25 °N and 40 °N) and southern Europe, Mediterranean, and Middle East regions. This multi-model approach predicts the transition to a more arid climate in these regions will begin in the late 20th century, and early 21st century. The models indicate that precipitation and evaporation will both decrease in these areas, however precipitation will decrease by a larger amount. Models predict that drying in the southwestern United States is will be caused by an increase in humidity, which causes an increase in moisture divergence, and changes in atmospheric circulation cells that include an expansion poleward of subtropical dry zones (Seager et al. 2007).

ENSO is the most notable teleconnection that influences precipitation in North America (Zimmerman et al. 2015). Six multi-year droughts that were factored into the models in the IPCC fourth assessment report attribute variations in SST in the Pacific, such as La Nina events to these droughts. This multimodal assessment predicts that droughts in the southwestern United States will still occur during persistent La Nina events and become more intense overtime (Seager et al. 2007).

Statistical prediction models that investigate lagged relationships between regional precipitation amounts and atmospheric and oceanic conditions warrant attention as an approach to investigating how ENSO effects precipitation over Texas estuaries. The Niño Index Phase Analysis (NIPA) is a statistical model used to forecast hydroclimatic variables on a seasonal time scale. NIPA divides ENSO into phases and operates under the hypothesis that ENSO is affecting the state of the atmospheric- oceanic system, and relevant teleconnections depend on these changes in mean state.

The NIPA model was used to predict rainfall over the Lavaca-Colorado River Basin (LCRB) based on prior season atmospheric and oceanic variables. The NIPA model found that the strength of a La Niña or El Niño event is a good predictor of spring-time precipitation in the

LCRB. The NIPA model divides historical precipitation data for the Lavaca-Colorado River Basin into four distinct phases and correlates them with phases of ENSO. North American seasonal precipitation predictability has been associated with distinct phases of ENSO, and the NIPA model can be used to predict how ENSO will affect precipitation over this area during El Niño events, and La Niña events as well as in between El Niño and La Niña events. Being able to predict precipitation, on a decadal scale is imperative to buffering impacts induced by climate change (Zimmerman et al. 2015).

Under varying climatic scenarios, changes in climate cause changes in bay salinity, (Tunnel et al. 2007). ENSO impacts estuarine salinity patterns across Texas with in a 4 to 6-month time frame. El Niño events are associated with increased precipitation and decreasing in salinity and La Niña events are associated with decreased precipitation and increasing salinities coast wide (Tolan 2007). Impacts from ENSO are present in other areas of the world as well. The Cienaga Grande de Santa Maria (CGSM)-Pajarles lagoon Complex is the largest coastal lagoon system in Columbia. Salinities in the lagoon system are influenced by freshwater inflow from the Magdalena River (Kaufmann & Hevert 2005). Freshwater inflow from the Magdalena River to CGSM is correlated with ENSO (Restrepo & Kjerfve, 2005). Salinity increases or decreases in this system are associated with the amount of freshwater inflow the system receives, which increases during El Niño events and decreases during La Niña events (Blanco et al. 2005). Changes in salinity impact estuarine organisms in both locations (Palmer et al. 2011; Blanco et al. 2005).

Estuarine organisms exhibit optimal salinity tolerances for growth, development and reproduction (Patillo et al. 1997). Changes in estuarine salinity caused by anthropogenic effects or ENSO can affect them (Tolan 2007). Changes in freshwater inflow are known to alter macroinfauna distribution, abundance, diversity (Kotta et al. 2009), and biomass (Palmer et al. 2011). Fresh water inflow, and corresponding salinity changes, are the main factors controlling distribution and diversity of macroinfaunal communities. Functional infauna diversity will decrease with changes in freshwater inflow because benthic infauna communities will acclimate to the changes in salinity, and more (or less) salt tolerant species dominate (Kim & Montagna, 2009; Montagna et al. 2002; Palmer et al. 2002; Atrill et al. 1996). In the current study similarities in macroinfauna communities between bays (Figure 6) were likely driven by similarities in salinity.

Salinity levels in the estuaries also affect mobile epifauna, which are potential predators of macroinfauna. In the current study salinity levels positively correlated with epifauna in the Lavaca-Colorado and Guadalupe Estuary, and not in the Nueces Estuary. This is due to the location of these estuaries along the salinity gradient.

Numerous studies show the effect of salinity concentration on mobile epifauna abundance in Texas vary by estuary. A drought study showing how estuarine organisms respond during periods of low precipitation and high salinity showed that abundance of brown shrimp (*Farfantepenaus aztecus*) increased when inflow conditions were at baseline in the Guadalupe and Lavaca-Colorado Estuaries, and increased in baseline and drought conditions. White shrimp abundance sampled in this study was positively correlated with inflow and tended to decrease in abundance and spatially in drought periods (Palmer & Montagna 2015). In the CGSM a period of prolonged salinity increase caused mass fish kills in the 1990's (Blanco et al. 2005). Total numbers of epifauna sampled in the current study were influenced by salinity. Overall more epifauna was sampled in the primary bays (where the salinity is higher due to influence from the Gulf of Mexico) than the secondary bays (closest to the estuary's freshwater source) (Table 5 and Figure 10).

Over the course of the current 22-year study benthic abundance declines in the Lavaca-Colorado, Guadalupe and Nueces Estuaries. Benthic biomass in the Lavaca-Colorado Estuary and the Nueces Estuary showed declining trends as well (Figs.7 and 8). This indicates that the results of Pollack et al. (2011) are not isolated to the Lavaca-Colorado Estuary, but are happening regionally as well.

Predation from mobile epifauna may influence declining infauna trends. Predators of macroinfaunal communities include Black Drum, Red Drum, Blue Crab and White Shrimp (Palmer & Montagna, 2015; Kim & Montagna, 2009). However declining infauna trends due to predation was not evident in this current study. Predation effects were assumed to lead to an inverse correlation between epifauna abundance with infaunal abundance. Because the trends in infaunal abundance across all Texas estuaries are declining (Table 5), and there is not a significant relationship between infaunal abundance, and epifauna abundance (Table 7), it is likely that climate change is the main factor in benthic infauna community declines, and not predation.

Trends in infaunal biomass and epifaunal abundance and species richness were positively correlated in Upper San Antonio Bay (Table 5B.) This may be due to the bay's proximity to the Guadalupe River. Freshwater inflow from the Guadalupe River is a source of nutrient input for San Antonio Bay, and nutrient input from the Guadalupe River into San Antonio Bay is positively correlated with infaunal abundance (Montagna & Yoon, 1991). Lower salinity regimes are required to support food production for marine suspension feeders (Montagna and Li 2010). Because of this nutrient input, benthic abundance and biomass increase closer to the Guadalupe River (Montagna & Palmer 2011).

In addition to anthropogenic and naturally caused climate change, the resilience of infaunal and epifaunal communities can be impacted by human activities that reduce freshwater inflow (Montagna et al. 2013). The construction of dams and diversions of freshwater for human consumption will increase salinities, which can then lead to impacts on the macrobenthic communities in the secondary bays. Diversion of inflow to the Lavaca-Colorado Estuary would not have an impact on benthic infaunal diversity in the primary bay, however it would have negative effects on infaunal diversity in the secondary bay (Kim & Montagna, 2009). The difference in response between primary and secondary bays was attributed the primary bay's tidal exchange with the Gulf of Mexico. Benthos that live in primary bay, i.e., Matagorda Bay, were better acclimated to high salinities being near the Gulf of Mexico than benthos that live in secondary bay, i.e., Lavaca Bay, close to the Lavaca River.

Epifauna data was sampled using a trawl. Studies in the Irish Sea and Corpus Christi Bay demonstrate this sampling method disturbs bay sediment, and can have a negative effect on benthic infauna abundance, biomass, and species richness as well as epifauna abundance and species richness (Hinz et al. 2009; Wilber et al. 2008). This disturbance can disrupt benthic habitats at scales of 100's to 1000's of meters (Whitlach et al. 1998), and benthic habitats can take six months to recover from trawling (Wilber et al 2008). An existing theory in Jennings et al. 2001 study of the North Sea, and Whitlach et al. 1998 study of disturbance on bottom scale dynamics, states that frequent trawling of an area could impact the types of infauna sampled. Frequent trawling could lead to a proliferation of smaller benthic species with shorter life spans that are better adapted to be in frequently trawled areas (Jennings et al. 2001).

CONCLUSIONS

It is likely that global climate change is having a negative impact on benthos of Texas estuaries because the results of Pollack et al. (2011) were not isolated to the Lavaca-Colorado Estuary and infauna abundance was not correlated to epifaunal abundance. Further, the benthic declines are likely to continue because climate models predict changing precipitation around the world and that the western Gulf of Mexico will become more arid over time due to a decrease in precipitation (Zimmerman et al. 2015). If benthos continues to decline over time, it is also possible that population that feed on benthos will also eventually be threatened. Modeling climate and predicting precipitation amounts can help resource managers plan and adapt regulatory programs to ensure long-term maintenance of natural marine resources in Texas estuaries.

Human populations living in coastal watersheds have increased and will continue to do so, as a result fresh water will be diverted from estuaries to serve the growing populations, which can lead to further degradation of the estuaries. To prevent the degradation of estuaries resource management is becoming an important issue. Policies, such as Texas Senate Bill 3, and Texas Water Code 16.085(1), have been put in place to manage the amount of water Texas estuaries receive and seek to identify the optimal amount of freshwater inflow, necessary to sustain biological productivity and typical biodiversity patterns persist in the estuaries. Monitoring benthos to better determine the impacts of water diversion on Texas estuaries is needed.

REFERENCES

Attrill MJ, Rundle SD, Thomas R (1996) The influence of drought-induced low freshwater flow on an upper-estuarine macroinvertebrate community. Water Research 30:261–268

Alber M (2002) A conceptual model of estuarine freshwater inflow management. Estuaries 25:1246–1261

Beseres Pollack J, Palmer T, Montagna P (2011) Long-term trends in the response of benthic macrofauna to climate variability in the Lavaca-Colorado estuary, Texas. Marine Ecology Progress Series 436:67–80

Britton JC, Morton B (1989) Shore ecology of the Gulf of Mexico. University of Texas Press, Austin, TX, United States

Center NOAACP (2001) NOAA's Climate Prediction Center. Climate Prediction Center http://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php

Coastal Hydrology Coastal Hydrology | Texas Water Development Board http://www.twdb.texas.gov/surfacewater/bays/coastal_hydrology/index.asp

Colorado-Lavaca Bay/Basin Expert Science Team (2011) Environmental Flow Regimes Recommendations Report. Colorado and Lavaca Rivers and Matagorda and Lavaca Bays Basin and Bay Expert Science Team, Austin, TX, United States

Gershunov A, Barnett TP (1998) Interdecadal Modulation of ENSO Teleconnections. Bulletin of the American Meteorological Society 79:2715–2725

Hinz H, Prieto V, Kaiser MJ (2009) Trawl disturbance on benthic communities: chronic effects and experimental predictions. Ecological Applications 19:761–773

Kim H-C, Montagna PA (2009) Implications of Colorado river (Texas, USA) freshwater inflow to benthic ecosystem dynamics: A modeling study. Estuarine, Coastal and Shelf Science 83:491–504

Kim H-C, Son S, Montagna P, Spiering B, Nam J (2014) Linkage between freshwater inflow and primary productivity in Texas estuaries: Downscaling effects of climate variability. Journal of Coastal Research 68:65–73

Kotta J, Kotta I, Simm M, Põllupüü M (2009) Separate and interactive effects of eutrophication and climate variables on the ecosystem elements of the Gulf of Riga. Estuarine, Coastal and Shelf Science 84:509–518

Montagna PA, Gibeaut JC, Tunnell JW, Jr (2007) South Texas Climate 2100: Coastal Impacts. In: Norwine J, John K (eds), South Texas Climate 2100: Problems and Prospects, Impacts and Implications. p 57–77

Montagna PA, Li J (2010) Effect of Freshwater Inflow on Nutrient Loading and Macrobenthos Secondary Production in Texas Lagoons. In: Coastal Lagoons: Critical Habitats of Environmental Change, M. J. Kennish and H. W. Paerl (eds.), CRC Press, Taylor & Francis Group, Boca Raton, FL, pp. 513-539.

Montagna P, Vaughan B, Ward G (2011) The Importance of Freshwater Inflows to Texas Estuaries. In: Water Policy in Texas: Responding to the Rise of Scarcity, Griffin RC (e.d.). The RFF Press, Washington D.C., p 107–127

Nueces River and Corpus Christi and Baffin Bay Expert Science Team (2011) Environmental Flows Recommendation Report. Final Submission to the Environmental Flows Advisory Group, Nueces River and Corpus Christi and Baffin Bays Basin and Bay Area Stakeholders Committee, and Texas Commission on Environmental Quality

Palmer TA, Montagna PA (2015) Impacts of droughts and low flows on estuarine water quality and benthic fauna. Hydrobiologia 753:111–129

Palmer TA, Montagna PA, Pollack JB, Kalke RD, Deyoe HR (2011) The role of freshwater inflow in lagoons, rivers, and bays. Hydrobiologia 667:49–67

Rajagopalan B, Cook E, Lall U, Ray BK (2000) Spatiotemporal variability of ENSO and SST Teleconnections to summer drought over the United States during the twentieth century. Journal of Climate 13:4244–4255

Rassumson EM, Carpenter TH (1982) Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. Deep Sea Research Part B Oceanographic Literature Review 29:759

Texas Department of Water Resources (1981) Guadalupe Estuary: An analysis of bay segment boundaries, physical characteristics, and nutrient processes.

Texas Water Development Board (TWDB) (2017) https://waterdatafortexas.org/coastal/hydrology accessed September 2017.

Tolan JM (2007) El Niño-Southern Oscillation impacts translated to the watershed scale: estuarine salinity patterns along the Texas Gulf Coast, 1982 to 2004. Estuarine Coastal Shelf Science 72: 247–260

Tunnell JW, Jr, Dokken, QR, Smith EH, Withers K (1996) Current Status and Historical Trends of the Estuarine Living Resources within the Corpus Christi Bay National Estuary Program Study Area. Corpus Christi Bay National Estuary Program Report No. CCBNEP-06A, Texas Natural Resource Conservation Commission, Austin, TX

Wilber DH, Ray G, Clarke DG, Diaz RJ (2008) Responses of Benthic Infauna to Large-Scale Sediment Disturbance in Corpus Christi Bay, Texas. Journal of Experimental Marine Biology and Ecology 365:13–22

Wilber D, Bass R (1998) Effect of the Colorado River Diversion on Matagorda Bay Epifauna. Estuarine, Coastal and Shelf Science 47:309–318