# Linkage between Freshwater Inflow and Primary Productivity in Texas Estuaries: Downscaling Effects of Climate Variability

Authors: Kim, Hae-Cheol, Son, Seunghyun, Montagna, Paul, Spiering, Bruce, and Nam, Jungho

Source: Journal of Coastal Research, 68(sp1) : 65-73

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/SI68-009.1

Journal of Coastal Research | SI | 68 | 65-73 | Coconut Creek, Florida | 2014

# Linkage between Freshwater Inflow and Primary Productivity in Texas Estuaries: Downscaling Effects of Climate Variability

www.cerf-jcr.org

**Hae-Cheol Kim[†], Seunghyun Son[‡], Paul Montagna[§], Bruce Spiering[**], and Jungho Nam[‡‡*]**

[†]I.M.Systems Group at Environmental Modeling Center, NCEP/NOAA, College Park, MD 20740 U.S.A.

[‡]Cooperative Institute for Research in the Atmospheric at Colorado State University Fort Collins, CO 80523, U.S.A.

[§]Harte Research Institute for Gulf of Mexico Studies, Texas A&M University at Corpus Christi, Corpus Christi, TX 78412, U.S.A.

[**]Applied Science and Technology Project Office, SSC/NASA, Stennis Space Center MS 39529, U.S.A.

[‡‡]Korea Maritime Institute, Sang-Am Dong Seoul, South Korea

## ABSTRACT

www.JCRonline.org

Kim, H.; Son, S.; Montagna, P.; Spiering, B. and Nam, J., 2014. Linkage between freshwater inflow and primary productivity in Texas estuaries: Downscaling effects of climate variability. *In:* Huang, W. and Hagen S.C. (eds.), *Climate Change Impacts on Surface Water Systems*. Journal of Coastal Research, Special Issue, No. 68, pp. 65-73. Coconut Creek (Florida), ISSN 0749-0208.

The estuaries of Texas are lagoons that lie in a climatic gradient in the northwestern Gulf of Mexico (GOM). Estuaries located in the northeastern part of the Texas coast receive more rainfall than estuaries in the southwestern part, and consequently greater runoff and concomitant freshwater inflow. Extreme inter-annual variability of precipitation caused by El Niño Southern Oscillation (ENSO) events is another characteristic of the Texas coast. During El Niño periods, salinities in Texas estuaries decrease because of increased precipitation and increased freshwater inflow to the coast. During La Niña periods, salinities increase due to drier climatic conditions and reduced freshwater inflow. The combination of the climatic gradient and temporal variability of freshwater inflow drive changes in the frequency, timing, duration, and magnitude of river flows to coastal waters, which in turn control the salinity, nutrients, organic matter, and sediments in Texas estuaries. Chlorophyll biomass, as an indicator of primary production, was estimated from Moderate Resolution Imaging Spectroradiometer (MODIS) data from July 2002 to December 2011 for all Texas estuaries. The climate patterns in the Pacific Ocean delivers a cascading signal via freshwater inflow changes to estuaries that effects primary production subsequently. The maximum correlation was found at the 5th lag (month) with correlation coefficient ($\rho$) being 0.45 (NIÑO3.4 is fixed as a reference). The combination of the local climatic gradient and quasi-periodic natural variability in ENSO has been influencing estuarine ecosystem dynamics over decadal scales in this region. The present study demonstrates that freshwater inflow is an important driver in maintaining primary productivity of Texas estuaries, which is required to maintain estuarine health and sustainability.

**ADDITIONAL INDEX WORDS:** *ENSO, MODIS, tele-connection, climatic gradient, chlorophyll, ecosystem responses.*

## INTRODUCTION

The Texas coast is located in the northwestern Gulf of Mexico between subtropical latitudes (26° N and 30° N), which experiences high evaporation rates (Larkin and Bomar, 1983). There is also a climatic gradient along the Texas coast where there are wetter conditions in northeastern estuaries and dryer conditions in southwestern estuaries (Longley, 1994; Montagna *et al.,* 2007). Along this longitude gradient, rainfall decreases by a factor of two from 142 cm $\text{year}^{-1}$ near Louisiana border (93.7° W) to 69 cm $\text{year}^{-1}$ near the US-Mexico border (97.6 ° W) in WGOM (Larkin and Bomar, 1983), resulting in a decrease of freshwater inflow (FWI) about 1.5 orders of magnitude. Because of the gradient of FWI balance, the Texas coast experiences dramatic changes in salinity with characteristic salinity regimes (positive – neutral – negative) from north to south (Tolan, 2007). The Texas coastal plain is also flat and low-lying with one of the highest rates of subsidence in the world (Anderson, 2007). Therefore, potential changes in precipitation patterns with climate change are a major driver in the water-cycle that influences Texas estuarine systems.

The timing, frequency, duration, and magnitude of river inflows to the Texas coast are also highly variable from year to year (Montagna *et al.,* 2002, 2011). Precipitation and temperature patterns in the southern United States are correlated with episodic events of El Niño and La Niña (Montroy, 1997; Montroy *et al.,* 1998; Ting and Wang, 1997). In particular, precipitation and temperature patterns during the cold season (October – March) in the southwestern United States are highly variable and closely correlated with climate events driven by El Niño Southern Oscillation (ENSO). This tele-connection is well documented (Cayan *et al.,* 1999; Gershunov and Barnett, 1998; Hong and Kalnay, 2002; Kiladis and Diaz, 1989; Ropelewski and Halpert, 1986, 1996; Wallace *et al.,* 1992). During El Niño events, Pacific moisture trapped in the upper atmosphere is

---

*DOI: 10.2112/SI68-009.1 received 29 March 2014; accepted in revision 18 July 2014.*

[*] Corresponding author: jhnam@kmi.re.kr

[**] Retired

delivered to the southwestern United States, which results in increased precipitation and thus increased FWI to coasts and freshening of Texas estuaries (Tolan, 2007). During La Niña periods, salinities increase because of the drier climatic conditions relative to normal years. The teleconnection of the ENSO signal to local watersheds and salinities in Texas estuaries is lagged by 4 months with the Southern Oscillation Index (SOI) and 6 months with ENSO, respectively (Tolan 2007).

The effects of climatic and FWI variability on coastal environments and ecosystems of the northwestern Gulf of Mexico has been documented in earlier studies (Twilley *et al.,* 2001). Coastal habitat area changes in Texas with changes in precipitation and FWI (Longley, 1995; Montagna *et al.,* 2007). Sea level rise will drive changes in productivity (Zimmerman *et al.,* 1991). Sea surface temperature has increased while dissolved oxygen has decreased since 1977 in Texas bays (Appelbaum *et al.,* 2005, Montagna *et al.,* 2011). Biomass and vegetative cover of estuarine marsh plants are correlated to precipitation events (Dunton *et al.,* 2001). Long-term changes in climatic settings and FWI have been correlated to changes in macrobenthic community structure (Pollack *et al.,* 2009, 2011) and changes in productivity and functional diversity of benthos (Kim and Montagna, 2009, 2012). FWI and climatic gradients are also correlated with nutrients and primary productivity (Palmer *et al.,* 2011). However, many of these studies are limited in spatial extent or spatial resolution.

The goal of the present study is to quantify effects of FWI dynamics on primary production along the Texas coast using large spatial coverage. Existing field data sets are valuable but they are not sufficient to investigate effects of climate-driven land-ocean coupling processes and subsequent ecosystem responses with a high degree of spatial resolution or regional spatial coverage. In contrast, satellite imagery is ideal for this purpose. The present study will address: 1) how the combination of local climatic gradient and quasi-periodic natural variability in ENSO influence the estuarine phytoplankton ecosystem dynamics over a decade in this region; 2) the implications of spatio-temporal effects of climate change in the Texas estuarine ecosystems; and 3) the possibility of climate-scale ecological forecasts focusing on primary productivity.

## MATERIALS AND METHODS

Texas estuaries are lagoons, which are shallow (2 – 3 m) and separated from the Gulf of Mexico by barrier islands. The estuaries are composed of two bay systems where primary bays are marine settings connected to the Gulf of Mexico and secondary bays are brackish settings connected to rivers (Figure 1). The major bay-estuarine systems included in this study are Lavaca-Colorado Estuary, Guadalupe Estuary, Mission-Aransas Estuary, Nueces Estuary, and Laguna Madre Estuary. Laguna Madre is divided into upper and lower systems. These estuarine systems are often named after their primary bay, such as Matagorda (MB), San Antonio (SA), Aransas (AB), Corpus Christi (CC), and Upper (ULM) and Lower Laguna Madre Bay (LLM), respectively (Orlando *et al.,* 1993). Abbreviated names of primary bays are used hereafter. Coordinates of the estuary delineations for obtaining satellite imagery are given in Table 1.

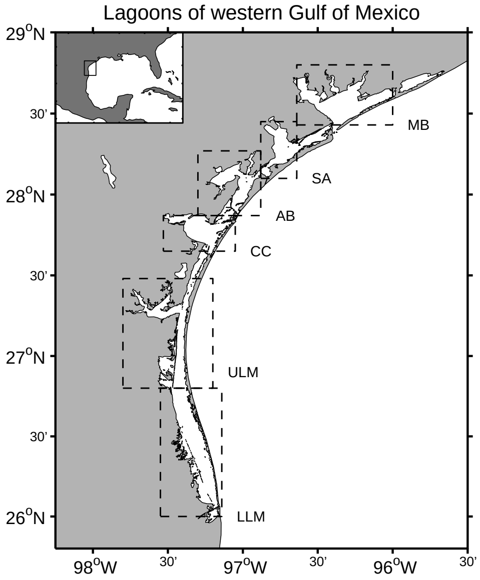

Figure 1. Map of Texas estuaries used in the study. Bay name abbreviations: Matagorda (MB), San Antonio (SA), Aransas (AB), Corpus Christi (CC), and Upper (ULM) and Lower Laguna Madre Bay (LLM). Coordinate delineations given in Table 1.

Table 1. *Locations and boundaries of the delineated estuarine bay systems*

| Bay System | Latitude Range | Longitude Range |
|---|---|---|
| Matagorda Bay | 28.45°N - 28.80°N | 96.00°W - 96.63°W |
| San Antonio Bay | 28.10°N - 28.50°N | 96.64°W - 96.88°W |
| Aransas Bay | 27.95°N - 28.27°N | 97.20°W - 96.89°W |
| Corpus Christi Bay | 27.65°N - 27.90°N | 97.53°W - 97.05°W |
| Upper Laguna Madre | 26.80°N - 27.48°N | 97.80°W - 97.35°W |
| Lower Laguna Madre | 26.00°N - 26.80°N | 97.50°W - 97.14°W |

Ocean color data from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Aqua platform have been provided by the Ocean Biology Processing Group (OBPG) at the National Aeronautics and Space Administration (NASA). The MODIS sensor has been operating since July 2002 until present (of this writing). The daily MODIS-Aqua level-2 chlorophyll *a* (Chl-*a*) reprocessing version 2012.0 (http://oceancolor.gsfc.nasa.gov/WIKI/OCReproc20120MA.html) data over a 9.5-year period from July 2002 to December 2011 covering the Texas estuaries and the northwest Gulf of Mexico (NWGOM) were obtained from the NASA OBPG website (http://oceancolor.gsfc.nasa.gov). The Chl-*a* products were retrieved using the NASA standard chlorophyll algorithm for the MODIS-Aqua data (OC3M-547, http://oceancolor.gsfc.nasa.gov/REPROCESSING/R2009/ocv6/) , which is updated from O'Reilly *et al.* (1998). Daily level-2 data were remapped to a standard Mercartor projection method at 1.0-km resolution after applying 3 flags (high sun glint; high solar zenith angle; high sensor zenith angle) using the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Data Analysis System SeaDAS), which is ocean color data processing software provided by the NASA OBPG. The remapped data were used to generate time series data and images for monthly climatology.

An empirical orthogonal function (EOF) analysis was performed over the long-term time series of monthly Chl-*a* data from six estuaries. EOF analysis is also known as a principal component analysis (PCA) applied to a group of time series data sets. A new time series of coherent variations (i.e., temporal sample scores) was created from the original time series and an eigenvector of covariance matrix (i.e., estuary spatial loadings) was created for the six estuaries. Non-complex EOF was used assuming that the original time series does not involve time lags among sites, which means that measurements at a certain time are considered being a synoptic snapshot.

The time series of coherent variation (i.e., scores) for the major principal component (PC 1 or EOF mode 1) was then filtered removing seasonality in order to focus on inter-annual variability; and was compared against one ENSO index (NINÑO3.4) using cross-spectral analysis (XCF) in order to compute time lags between the two time series. The NIÑO3.4 index is the climate index defined by differences in average sea surface temperature (SST) over the region of 5° S - 5° N and 170° W - 120° W. This region has large variability on El Niño time scales, and is close to the region where changes in local sea-surface temperature is important for shifting the large region of rainfall typically located in the far western Pacific. An El Niño or La Niña event is identified if the 5-month running-average of the NIÑO3.4 index exceeds +0.4 °C for El Niño or -0.4 °C for La Niña for at least 6 consecutive months (Trenberth, 1997). Monthly NIÑO3.4 data (version ERSST.V3B; www.cpc.ncep.noaa.gov/data/indices/) were obtained from the Climate Prediction Center (CPC) of National Centers for Environmental Prediction (NCEP) at National Oceanic and Atmospheric Administration (NOAA).

## LONG-TERM TIME-SERIES AND SPATIAL PATTERN

Monthly Chl-*a* concentrations have different seasonal distributions among the six estuaries (Figure 2a). The seasonal variations of Chl-*a* from northeastern estuaries (MB, SA, and AB) have relatively higher concentrations during late spring to fall season (April – October), and lower values during the winter months (November – March). An exception to this pattern is that SA has lower Chl-*a* values in summer. In contrast, the southwestern estuaries (CC, ULM, and LLM) have the opposite trend with higher Chl-*a* concentrations during late fall to spring season (September – March). The different patterns imply that there is a difference in local environmental conditions among the estuaries, which is likely caused by different seasonal patterns of freshwater discharge.

The mean Chl-*a* concentration also has two patterns significantly different between northern and southern estuaries ($p<0.01$). There is a higher chlorophyll concentration in northeastern estuaries (MB, SA and AB) than in southwestern estuaries (CC, ULM and LLM) (Figure 2b). The 9.5-year mean Chl-*a* concentration in northeastern estuaries ranges from 8.74 to 9.51 mg Chl $m^{-3}$. Estuaries located further southwest have a range of 2.73 and 4.03 mg Chl $m^{-3}$, which is two to three times smaller than those from north. This gradient of Chl-*a* along the Texas coast is correlated to that of inflow balance which decreases from northeast to southwest (Longley, 1995), and differences in nutrient loading (Palmer *et al.,* 2011).

The time-series of a Chl-*a* anomalies in six estuaries reveal that there is a year-to-year variation in Chl-*a* concentration tightly coupled with NINÑO3.4 (Figs. 3a-3f). This regional interannual variability can be attributed to links to quasi-periodic global climate events, such as ENSO, because during El Niño event increased precipitation and FWI in the area brings more nutrients to the coasts, resulting in increased estuarine phytoplankton biomass; whereas, during La Niña events drier climatic conditions are associated with a reduced supply of nutrients to phytoplankton.

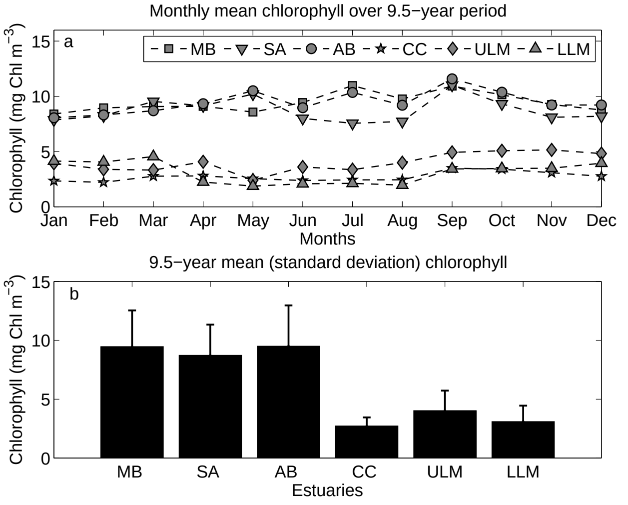

Figure 2. Monthly average of daily MODIS-derived chlorophyll concentrations between July 2002 and December 2011 for each estuary as defined in Figure 1. Monthly averages (a), and estuary-wide averages (b).

A Hovmöller diagram, representing temporal evolution of Chl-*a*, presents a temporal profile of alternating patterns between positive (red) and negative (blue) anomalies (Figure 3g). This implies that interannual variability of Chl-*a* is driven by quasi-periodic ENSO events of certain time intervals. The patterns sometimes reveal strong positive or negative signals (dark red or blue colors) in all six estuaries or sometimes weak signals (light red or blue) reaching only some estuaries indicating that the magnitude of ENSO's influence on local estuaries varied with different spatial scales due to different local climate, environmental and ecological conditions.

Chl-*a* concentrations were much greater in coastal waters off the barrier islands during El Niño periods as compared to La Niña periods (Figure 4). For example, ocean color imagery derived from MODIS shows that Chl-*a* values from El Niño year 2004 (Figure 4a) are at higher levels than those from La Niña year 2008 (Figure 4b). The same is true inside of barrier islands and on coastal regions of the coast. The similarity of the estuarine and coastal patters implies that changes in FWI and subsequent Chl-*a* driven by ENSO events are quite extent, not limited within estuaries.

## DECOMPOSITION OF CLIMATE INDEX AND TIME-SERIES

An EOF analysis was applied to compute eigenvector and eigenvalues of covariance that can explain variability of the time-series data set, i.e., the 9.5-year Chl-*a* concentrations from six estuaries (Figure 5). As all principal components are decomposed into their orthogonal position, variation of Chl-*a* time series can be interpreted by examining vector biplots of two major principal components, PC 1 (EOF mode 1) and PC 2 (EOF mode 2), which represents temporal and spatial structure of the data. (Figure 5). The eigenvector (or loadings) for the six estuaries are represented with lines (Figure 5a). The individual temporal samples are represented by dots (Figure 5b) with keys (months since July 2002) next to symbols (Figure 5c). All six estuaries are located on the positive side of PC 1 axis, which is interpreted as the temporal component. The distribution of variables along PC 2 axis (interpreted as the spatial component) separates northeastern estuaries (MB, SA and AB) from southwestern estuaries (CC, ULM and LLM) having opposite signs of PC 2, which is related to the aforementioned climatic gradient in this region. It is noteworthy that CC falls out separately from the other two (ULM and LLM) despite the fact that it has the same sign as ULM and LLM. This indicates that the temporal structure between El Niño and La Niña year in CC was not as distinctive as those in ULM and LLM. PC 1 and PC 2 can explain the variance of the original time series 51% and 18%, respectively. Thus 69% of the variance of the 9.5-year time series of MODIS-derived Chl-*a* from estuaries along Texas coast can be explained in terms of temporal (inter-annual variability) and spatial (north and south) structure by the first two principal components.

A Fast Fourier Transform (FFT) of the climate index and estuarine-wide Chl-*a* time series reveal frequencies with high spectral power (Figure 6). The detrended NIÑO3.4 has a few significant (95% CI) bands at around 0.25 to 0.9, which can be converted to periodicities of 1 to 4 years (Figure 6a). Similarly, EOF mode 1 (PC 1), that explains variance by 51%, shows high spectral power at low frequency bands (< 0.5 year$^{-1}$), specifically at around 0.4 (2.5 years) (Figure 6b). Power spectral structure of EOF mode 2 (PC 2), that can explain 18% of variance, was somewhat different from that of EOF mode 1, having high power at bands around 0.3 (3.3 years) and 0.8 (1.25 years) (Figure 6c). This is because EOF mode 2 is related to more or like spatial variability.

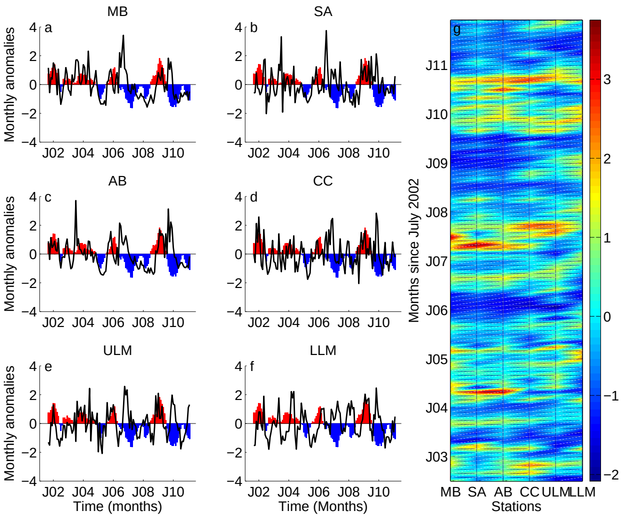

Figure 3. Anomalies of 9.5-year monthly chlorophyll (solid black lines) and NIÑO3.4 with positive (El Niño) and negative (La Niña) phase represented in red and blue bars, respectively for each of the six estuaries (a-f). A Hovmöller diagram showing temporal evolution of 9.5-year anomalies of Chl-*a* over six estuaries where red and blue color represents positive and negative anomalies, respectively (g).

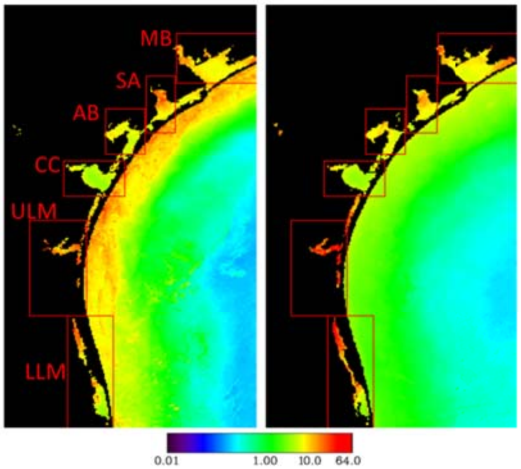

Figure 4. An example of MODIS-derived chlorophyll (mg Chl m$^{-3}$) for El Niño in 2004 (a) and La Niña in 2008 (b).

## CLIMATE IMPLICATIONS IN LONG-TERM TIME-SERIES

Variation of PC 1 (EOF mode 1), after detrending, is compared to the detrended NIÑO3.4 time series (Figure 7a). There are phase lags between the coherence variation of PC 1 (EOF mode 1) and the NIÑO3.4 anomaly. The cross-spectrum between the Chl-*a* and NIÑO3.4 time series, having the same frequency with a phase-shift, gives exactly the same power spectrum structure as that from individual time series except that the former has a non-zero phase difference with a high power at a spectral frequency band of 0.4 (2.5 years) and 0.5 (2 years) (Figure 7b). The coherence spectrum, which shows correlation coefficient of the two time series at spectral frequency bands, also reveals high estimated coherency at bands around 0.25 (4 years), 0.4 (2.5 years), and 0.5 (2 years) (Figure 7c). The sign of the cross-correlation function at zero lag is positive (Figure 7d), which means that the relation between PC 1 and NIÑO3.4 is positively correlated with climate signal (NIÑO3.4) leading local response (PC 1), and maximum correlation was found at the 5th lag (month) with correlation coefficient (ρ) being 0.45 (NIÑO3.4 is fixed as a reference). This positive correlation is comparable to those 4 and 6 months that Tolan (2007) found from cross-correlation salinity had with SOI and ENSO, respectively.

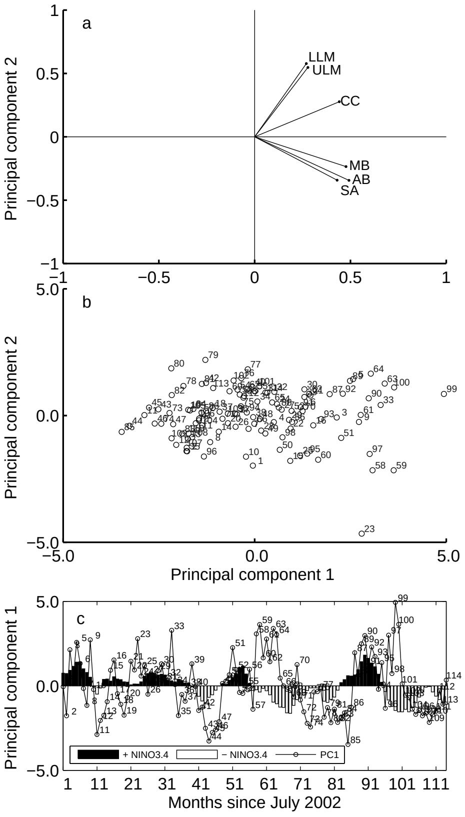

Figure 5. Principal component analysis (PCA) of Chl-*a* concentrations for spatial (estuaries) variables and temporal samples. Vector loads for estuaries (a), scores of PC 1 and PC 2 for sample dates (b), and a time-series of scores (PC 1) with NIÑO3.4 index (c). Notice that figure legends in (b) and (c) have keys (months since July 2002) next to symbols.

## ENSO AND FWI IN TEXAS ESTUARIES

There is a climatic gradient of decreasing rainfall and concomitant FWI from northeast to southwest along the Texas coast that influences FWI to estuaries. Rainfall decreases by a factor of two and inflow decreases by about two orders of magnitude. For example, inflow balance in Sabine Lake is 17 billion $m^3$ $year^{-1}$ whereas inflow balance in Laguna Madre has -0.9 billion $m^3$ $year^{-1}$ (Longley, 1994; Texas Water Development Board http://www.twdb.texas.gov/surfacewater/bays/coastal_hydrology/index.asp). Consequently, this pattern of FWI results in a distinctive gradient in salinity patterns along the Texas coastline ranging from oligohaline to hypersaline (Montagna *et al.,* 2011; Tolan, 2007).

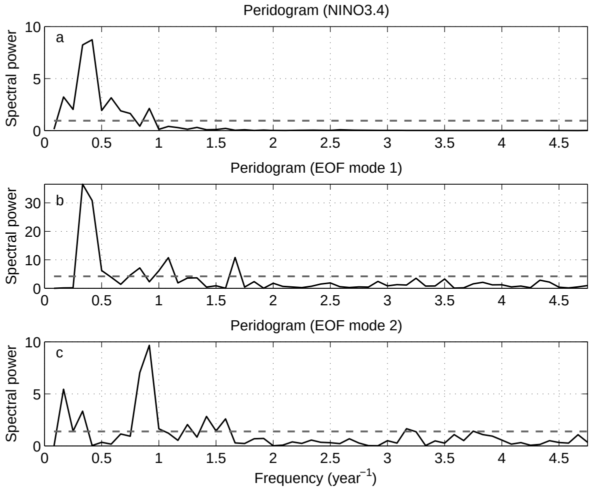

Figure 6. Peridograms of climate index, NIÑO3.4 (a), and EOF mode 1 (b) and EOF mode 2 (c). Horizontal grey dashed lines represent upper limits of 95% confidence interval.

Winter season (October – March) precipitation and temperature patterns in southwestern United States are highly correlated with ENSO events (Cayan *et al.,* 1999; Gershunov and Barnett, 1998; Hong and Kalnay, 2002; Kiladis and Diaz, 1989; Ropelewski and Halpert, 1986, 1996; Wallace *et al.,* 1992;). The Pacific jet stream delivers Pacific moisture to North America and changes its strength and meandering pattern (location) depending on atmospheric pressure systems over the eastern Pacific. During El Niño events the jet stream is strengthened by strong low pressure systems (increased thunderstorms), which makes a persistent and extended subtropical jet stream over the southwestern United States. As a result, the southwestern United States is wetter than normal during El Niño periods. This pattern of persistent storm activity becomes more variable and switches to northern mid-latitudes during La Niña events because the strong high pressure system sitting over the eastern Pacific Ocean blocks the extension of the subtropical jet stream. As a result, the Pacific Northwest is wetter than normal during La Niña. These dynamics are well documented and illustrated in the following link (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensocycle/nawinter.shtml).

Results of the present study demonstrate that primary productivity, as indicated by Chl-*a* concentrations are linked to inter-annual variability of climate patterns in the Pacific Ocean (Figure 3). The global scale climate effects deliver a cascading signal via FWI (and thus, nutrient loadings and salinity changes) to local estuarine primary production (Figure 4). The teleconnection is associated with 5 month-lags, which is comparable to 4- to 6-month lead by ENSO and SOI described by Tolan (2007).

## FWI CHANGES AND ECOSYSTEM STRUCTURE AND FUNCTION

Freshwater inflow dilutes salt content of estuaries and drives estuarine productivity, ecosystem health, and sustainability because river flow transports inorganic and organic nutrients from watersheds to coastal embayments (D'Avanzo *et al.,* 1996; Kemp *et al.,* 1997; Caffrey, 2004). Inorganic nutrients originating from upstream riverine flows are consumed by estuarine phytoplankton (primary producers) for photosynthesis and increased nutrients are associated with increased rates of primary production (Fisher *et al.,* 1992; Gallegos *et al.,* 1992; Jordan *et al.,* 1991; Lorentz *et al.,* 1990; 1994, 1997; Malllin *et al.,* 1993; Randall and Day, 1987). Photosynthetic parameters (P-I parameters), such as the maximum photosynthetic capacity ($P^{b}_{max}$) , photosynthetic efficiency ($\alpha^{b}$) and light adaptation ($I_k$) are governed by river outflow in the Gulf of Mexico because of changes in salinity, nutrients, mixed layer depth, and attenuation coefficients (Lorentz *et al.,* 1994). In Lavaca Bay, Texas, Chl-*a* concentrations increased during high flow indicating that primary production in enhanced by nutrient loadings (Kalke and Montagna 1991).

Nutrient enrichment often deteriorates water quality in coasts (Howarth, 2004; Bricker *et al.,* 2007). In particular, anthropogenically-derived nutrients have been a growing concern as environmental stressors that degrade water quality in coastal communities (Bricker *et al.,* 2007; Cloern, 2001; Diaz and Rosenberg, 2008; Nixon, 1995; Rabalais *et al.,* 1994; Vitousek *et al.,* 1997). In the Gulf of Mexico area, primary production in shelf waters near the Mississippi delta are significantly correlated with river-borne nitrate ($NO_3^-$) and nitrite ($NO_2^-$) (Lorentz *et al.,* 1997). The major source of nitrogen is fertilizer applied in agriculture, and the demise of phytoplankton that utilizes anthropogenic nutrients is sedimented and eventually causes harmful effects on benthic ecosystems because of hypoxic conditions (Justic *et al.,* 1993; Rabalais *et al.,* 1996; Turner and Rabalais 1994). Increased FWI is correlated with increased nutrients in receiving waters. Land cover/land use changes by human activities are linked to varying nutrient loadings and subsequent ecosystem responses in Texas coastal waters (Arismendez *et al.,* 2009; Palmer *et al.,* 2011; Pollack *et al.,* 2009).

One consequence of altered FWI regimes is change of benthic community structure within estuaries. Salinity gradients drive differing benthic community structure and diversity (Remane and Schlieper, 1971, Pollack *et al*., 2009). Changes in benthic community structure result from differences in physiological tolerance of benthic species and ecological function because altered nutrient loadings caused by altered FWI affect both estuarine primary production in the overlying water column and macrobenthic secondary production dependent on primary production (Montagna and Kalke, 1992; Kim and Montagna, 2009; 2012). Therefore, FWI changes, which are climate-driven, have cascading effects in estuarine ecosystems by changing phytoplankton (primary producers) growth, which stimulates secondary production by secondary producers (*e.g.*, zooplankton and benthic suspension feeders), and is followed by changes in tertiary production by organisms such as shrimps and fishes. This translation of climatic effects to estuarine productivity will certainly have socio-economical impact on human beings, the final consumers.

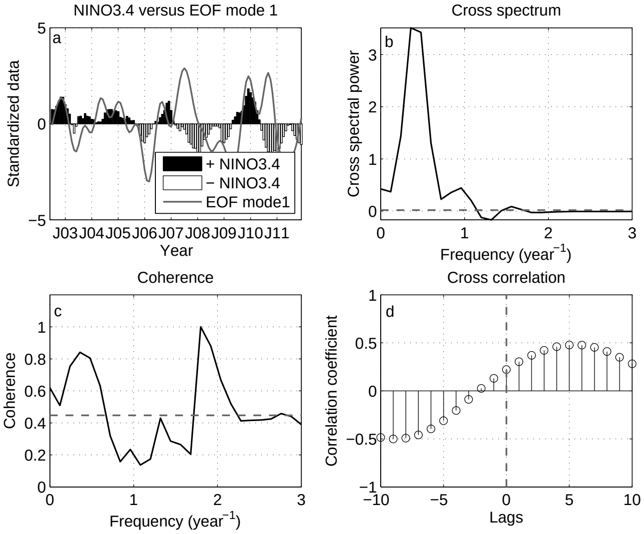

Figure 7. (a) EOF mode 1 (PC 1) versus NIÑO3.4, (b) cross spectral power between PC 1 and NIÑO3.4 at given spectral frequency bands, (c) coherence showing correlation coefficients between PC 1 and NIÑO3.4 at spectral frequency bands, (d) cross-correlation function with respect to lags explaining phase-shifts. Horizontal grey dashed lines represent upper limits of 95% confidence interval. Vertical grey dashed line represents phase-shift zero.

Because the data set examined here is only nine years long, nothing can be inferred about decadal or multi-decadal climate variability, such as Pacific Decadal Oscillation (PDO) and North Atlantic Oscillation (NAO). However, there has been a long-term trend of increasing temperature and decreasing dissolved oxygen in Corpus Christi Bay (Applebaum *et al.,* 2005), Matagorda Bay (Pollack *et al.,* 2011), and other Texas bays and estuaries (Montagna *et al.,* 2011; Tolan and Fisher, 2009). Increases in water temperature in Texas estuaries since the early 1990's are correlated with the positive phase of NAO (warmer winter in the United States), which provides more favorable over-wintering conditions for larval recruitment and juvenile settlement of gray snapper (Tolan and Fisher, 2009). Altogether, these examples demonstrate that natural variability of the environmental settings play a major role in estuarine ecosystem structure and function.

## PREDICTING ECOSYSTEM DYNAMICS AND LOCAL MANAGEMENTS

Impacts on coastal environment of climate change have been discussed in many studies, most of which deals with very long-term impacts and their potential consequences (Hoegh-Guldberg and Bruno, 2010; Hughes *et al.*, 2003). While climate change and its impacts have been discussed in very explicit manners at global scale, not much attention has been drawn to explore practical implication for month-to-month or year-to-year management (a.k.a., practical managements) at local levels. Among practical management issues, land-based activity control might be the representative one (GESAMP, 2001) to reflect variation of FWI driven by climate change in coastal environmental management.

Precipitation in the western United States is related to SOI and the hydrologic lags through snow melting processes are reflected in stream flow responses at intervals of several months (Cayan *et al.,* 1999). Understanding the time lags between SOI and stream flow responses is useful for water resource management because of potential extreme climate conditions such as flood or drought. The periodicities of climate-scale variations should be included in water management planning in Texas bays and estuaries because calculation of firm yield and environmental flow does not consider climate-driven inter-annual variability of FWI tele-connected to global climatic changes (i.e. ENSO, PDO) (Tolan, 2007).

The 5-month lag of primary productivity related to climate propagation in the Pacific Ocean can be combined with ecosystem models (***e.g.***, Kim and Montagna, 2009; 2012) and seasonal climate forecasts provided by climate research entities (***e.g.***, Climate Prediction Center at NCEP/NOAA; http://www.cpc.ncep.noaa.gov) to address management questions such as “when is the pelagic and benthic estuarine ecosystem response to the recent or upcoming ENSO events going to happen?” or “is upcoming ecosystem change responding to recent ENSO event going to be extreme?,” or “if so, what is the direction of the extreme change?” This kind of prediction capability is an example of a potential useful decision-making tool that local managers can deploy when they consider ecosystem management-related plans and regulatory criteria.

## CONCLUSIONS

Effects of FWI dynamics on primary production along the Texas coast and estuaries in the northwestern Gulf of Mexico are subject to inter-annual variability of climate patterns in the Pacific Ocean that deliver a cascading signal via increased precipitation, runoff, and FWI to estuaries. The increased FWI changes nutrient loadings and salinity patterns in estuaries, which effects primary production with 5 month-lags. This trend indicates that the combination of the local climatic gradient and quasi-periodic natural variability in ENSO have been influencing the estuarine ecosystem dynamics over decadal scales in this region. These findings combined with seasonal climate forecasts available in the climate research community can be useful to address water resource and fisheries management questions.

## ACKNOWLEDGMENTS

The authors are grateful to anonymous reviewers for their constructive comments and suggestion. This publication was made possible, in part, by Korea Maritime Institute (KMI) as part of a funded research, “Ecological and Socio-Economic Impacts of Watershed Development on Coastal and Marine Areas” and, in part, by NOAA, Office of Education Educational Partnership Program award (NA11SEC4810001). Computational facilities were supported by Harte Research Institute and National Centers for Environmental Prediction at NOAA. Its contents do not necessarily represent the official views of the U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

## LITERATURE CITED

Arismendez, S.S.; Kim, H.; Brenner, J., and Montagna, P.A., 2009. Application of watershed analyses and ecosystem modeling to investigate land-water nutrient coupling processes in the Guadalupe Estuary, Texas. *Ecological Informatics*, 4, 243-253.

Anderson, J.B., 2007. *Formation and future of the upper Texas coast*. Texas A&M Press, 163p.

Applebaum, S., Montagna, P.A., and Ritter, C., 2005. Status and trends of dissolved oxygen in Corpus Christi Bay, Texas, U.S.A. *Environmental Monitoring and Assessment*, 107, 297-311.

Bricker, S., Longstaff, B., Dennison, W., Jones, A., Boicourt, K.,Wicks, C., and Woerner, J., 2007. *Effects of nutrients enrichment in the nation's estuaries: a decade of change*. NOAA Coastal Ocean Program Decision Analysis Series No. 26. National Centers for Coastal Ocean Science, Silver Spring, Maryland, 322p.

Caffrey, J.M., 2004. Factors controlling net ecosystem metabolism in U.S. estuaries. *Estuaries*, 27, 90–101.

Cayan, D.R.; Redmond, K.T., and Riddle, L.G., 1999. ENSO and hydrologic extremes in the western United States. *Journal of Climate*, 12, 2881–2893.

Cloern, J.E., 2001. Our evolving conceptual model of the coastal eutrophication problem. *Marine Ecology Progress Series*, 210, 223-253.

D’Avanzo, C.; Kremer, J.N., and Wainright, S.C., 1996. Ecosystem production and respiration in response to eutrophication in shallow temperate estuaries. *Marine Ecology Progress Series*, 141, 263–274.

Diaz, R.J. and Rosenberg, R., 2008. Spreading dead zones and consequences for marine ecosystems. *Science*, 321, 926-929.

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

Fisher, T.; Peele, E.; Ammerman, J., and Harding, L. Jr., 1992. Nutrient limitation of phytoplankton in Chesapeake Bay. *Marine Ecology Progress Series*, 82, 51–63.

Gallegos, C.L.; Jordan, T.E., and Correll, D.L., 1992. Event-scale response of phytoplankton to watershed inputs in a subestuary. timing, magnitude, and location of blooms. *Limnology and Oceanography*, 37, 813-828.

Gershunov, A. and Barnett, T.P., 1998. ENSO influence on intraseasonal extreme rainfall and temperature frequencies in the contiguous United States: Observations and model results. *Journal of Climate*, 11, 1575–1586.

GESAMP (IMO/FAO/UNESCO-IOC/WMO/WHO/IAEA/UN/ UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) and Advisory Committee on Protection of the Sea, 2001. *Protecting the oceans from land-based activities - Land-based sources and activities affecting the quality and uses of the marine, coastal and associated freshwater environment. Reports and Studies*. GESAMP No. 71, 162 p.

Hoegh-Guldberg, O. and Bruno, J.F., 2010. The impact of climate change on the world's marine ecosystems, *Science*, 328(5985), 1523-1528.

Hong, S. and Kalnay, E., 2002. The 1998 Oklahoma-Texas drought mechanistic experiments with NCEP global and regional models. *Journal of Climate*, 15, 954-963.

Howarth, R.W., 2004. Human acceleration of the nitrogen cycle: drivers, consequences, and steps towards solutions. *Water Science and Technology*, 49, 7–13.

Huges, T.P.; Bairdl, A.H.; Bellwood, D.R.; Card, M.; Connolly, S.R.; Folke, C.; Grosberg, R.; Hoegh-Guldberg, O.; Jackson, J.B.C.; Kleypas, J.; Lough, J.M.; Marshall, P.; Nyström, M.; Palumbi, S.R.; Pandolfi, J.M.; Rosen, B., and Roughgarden, J., 2003. Climate change, human impacts, and the resilience of coral reefs, *Science*, 301(5635), 929-933

Jordan, T.E.; Correll, D.L.; Miklas, J., and Weller, D.E., 1991. Long-term trends in estuarine nutrients and chlorophyll, and short-term effects of variation In watershed discharge. *Marine Ecology Progress Series*, 75, 121-132.

Justic, D.; Rabalais, N.N.; Turner, R.E., and Wiseman, W.J. Jr., 1993. Seasonal coupling between riverborne nutrients, net productivity and hypoxia. *Marine Pollution Bulletin*, 26, 184-189.

Kalke, R. and Montagna, P.A., 1991. The effect on freshwater inflow on macrobenthos in the Lavaca River delta and upper Lavaca Bay, Texas. *Contributions in Marine Science*, 32, 49-77.

Kemp, W.M., Smith, E.M., Marvin-Dipasquale, M., and Boynton, W.R., 1997. Organic carbon balance and net ecosystem metabolism in Chesapeake Bay. *Marine Ecology Progress Series*, 150, 229–248.

Kiladis, G.N. and Diaz, H., 1989. Global climatic anomalies associated with extremes in the Southern Oscillation. *Journal of Climate*, 2, 1069–1090.

Kim, H. and Montagna, P.A., 2009. Implications of Colorado River freshwater inflow to benthic ecosystem dynamics: A modeling study. *Estuarine, Coastal and Shelf Science*, 83, 491-504.

Kim, H. and Montagna, P.A., 2012. Effects of climate-driven freshwater inflow variability on macrobenthic secondary production in Texas lagoonal estuaries: A modeling study. *Ecological Modelling*, 235-236, 67-80.

Larkin, T.J. and Bomar, G.W., 1983. *Climatic atlas of Texas*. Texas Department of Water Resources, Austin, Texas, 151 p.

Longley, W.L., 1994. *Freshwater Inflows to Texas Bays and Estuaries: Ecological Relationships and Methods for Determination of Needs*. Texas Water Development Board and Texas Parks and Wildlife Department, Austin, Texas, 386p.

Longley, W.L. 1995. Estuaries. *In:* North, G.R.; Schmandt, J., and Clarkson, J. (eds.), *The impact of global warming on Texas: a report to the task force on climate change in Texas*. The University of Texas Press, Austin, Texas, pp. 88-118.

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

Lorentz, S.E.; Fahnenstiel, G.L., and Redalje, D.G. 1994. Spatial and temporal variations of photosynthetic parameters in relation to environmental conditions in coastal waters of the northern Gulf of Mexico. *Estuaries*, 17, 779-795.

Lorentz, S.E.; Fahnenstiel, G.L.; Redalje, D.G.; Lang, G.A.; Chen, X., and Dagg. M.J. 1997. Variations in primary production of northern Gulf of Mexico continental shelf waters linked to nutrient inputs from the Mississippi River. *Marine Ecology Progress Series*, 155, 45-54.

Mallin, M.A.; Paerl, H.W.; Rudek, J., and Bates, P.W. 1993. Regulation of estuarine primary production by watershed rainfall and river flow. *Marine Ecology Progress Series*, 93, 199-203.

Montagna, P.A.; Brenner, J.; Gibeaut, J., and Morehead, S. 2011. Coastal Impacts. *In:* Schmandt, J.; North, G.R., and Clarkson, J. (eds.), *The Impact of Global Warming on Texas, second edition*. University of Texas Press, Austin, Texas, pp. 96-123.

Montagna, P.A.; Gibeaut, J.C., and Tunnell, J.W. Jr., 2007. South Texas climate 2100: coastal impacts. *In:* Norwine, J. and John, K. (eds.), *The changing climate of south Texas 1900-2100: problems and prospects, impacts and implications*. Texas A&M University-Kingsville, pp 57-77.

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

Montagna, P.A.; Kalke, R.D., and Ritter, C., 2002. Effect of restored freshwater inflow on macrofauna and meiofauna in upper Rincon Bayou, Texas, USA. *Estuaries*, 25, 1436-1447.

Montagna, P.A.; Ward, G., and Vaughan, B., 2011. The importance and problem of freshwater inflows to Texas estuaries. *In:* Griffin, R. C. (ed.), *Water policy in Texas: responding to the rise of scarcity*. The RFF Press, Washington, D.C., pp. 107-127.

Montroy, D.L. 1997. Linear relation of central and eastern North American precipitation to tropical Pacific sea surface temperature anomalies. *Journal of Climate*, 10, 531–548.

Montroy, D.L.; Richman, M.B., and Lamb, P.J. 1998. Observed nonlinearties of monthly teleconnections between tropical

Pacific sea surface temperature anomalies and central and eastern North American precipitation. *Journal of Climate*, 11, 1812–1835.

Nixon, S.W. 1995. Coastal marine eutrophication: a definition, social causes, and future concerns. *Ophelia*, 41, 199-219.

O'Reilly, J.E.; Maritorena, S.; Mitchell, B.G.; Siegel, D.A.; Carder, K.L.; Garver, S.A.; Kahru, M., and McClain, C. 1998. Ocean color chlorophyll algorithms for SeaWiFS. *Journal of Geophysical Research*, 103, 24937–24953.

Orlando, S.P.; Rozas, L.P. Jr.; Ward, G.H., and Klein, C.J. 1993. *Salinity characteristics of Gulf of Mexico estuaries*. National Oceanic and Atmospheric Administration, Office of Ocean Resources Conservation and Assessment, Silver Spring, Maryland, 209p.

Palmer, T.A.; Montagna, P.A.; Pollack, J.B.; Kalke, R.D., and DeYoe, H.R., 2011. The role of freshwater inflow in lagoons, rivers, and bays. *Hydrobiologia*, 667, 49-67.

Pollack, J.B.; Kinsey, J.W., and Montagna, P.A., 2009. Freshwater Inflow Biotic Index (FIBI) for the Lavaca-Colorado Estuary, Texas. *Environmental Bioindicators*, 4, 153-169.

Pollack, J.B.; Palmer, T.A., and Montagna, P.A., 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.

Rabalais, N.N.; Turner, R.E.; Justic, D.; Dortch, Q.; Wiseman; W.J. Jr., and Sen Gupta, B.J., 1996. Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf. *Estuaries*, 19, 386-407.

Randall, J.M. and Day, J.W., 1987. Effects of river discharge and vertical circulation on aquatic primary production in a turbid Louisiana (USA) estuary. *Netherland Journal of Sea Research*, 21, 231-242.

Remane, A. and Schlieper, C., 1971. *Biology of brackish waters*. Wiley Inter-Science, New York, 373 p.

Ropelewski, C. and Halpert, M., 1986. North American precipitation and temperature patterns associated with El Niño/Southern Oscillation (ENSO). *Monthly Weather Review*, 114, 2353-2362.

Ropelewski, C. and Halpert, M., 1996. Quantifying Southern Oscillation—Precipitation relationships. *Journal of Climate*,, 1043–1059.

Ting, M. and Wang, H., 1997. Summertime U.S. precipitation variability and its relation to Pacific sea surface temperature. *Journal of Climate*, 10, 1853–1873.

Tolan, J.M., 2007. El Niño-Southern Oscillation impacts translated to the watershed scale: estuarine salinity patterns along the Texas Gulf coast, 1982 to 2004. *Estuarine, Coastal and Shelf Science*, 72, 247-260.

Tolan J.M. and Fisher, M., 2009. Biological response to changes in climate patterns: population increases of gray snapper (*Lutjanus griseus*) in Texas bays and estuaries. *Fisheries Bulletin*, 107, 36-44.

Trenberth, K.E., 1997. The definition of El Niño. *Bulletin of the American Meteorological Society*, 78, 2771-2777

Turner R.E. and Rabalais N.N., 1994. Coastal eutrophication near the Mississippi River delta. *Nature*, 368, 619-621.

Twilley, R.R.; Barron, E.J.; Gholz, H.L.; Harwell, M.A.; Miller, R.L.; Reed, D.J.; Rose, J.B.; Siemann, E.H.; Wetzel, R.G., and Zimmerman, R.J., 2001. *Confronting climate change in the Gulf coast region.* The Union of Concerned Scientists, Cambridge, Massachusetts, and Ecological Society of America, Washington, D.C.

Vitousek, P,M.; Aber, J.D.; Howarth, R.W.; Likens, G.E.; Matson, P.A.; Schindler, D.W.; Schlesinger, W.H., and Tilman, D.G., 1997. Technical report: human alteration of the global nitrogen cycle: sources and consequences. *Ecological Applications*, 7, 737-750.

Wallace, J.M.; Smith, C., and Bretherton, C.S., 1992. Singular value decompositions of wintertime sea surface temperature and 500-mb height anomalies. *Journal of Climate*, 5, 561–576.

Zimmerman, R.J.; Minello, T.J.; Klima, E.F., and Nance, J.M., 1991. Effects of accelerated sea-level rise on coastal secondary production. *In:* Bolton,H.S. and Magoon, O.T. (eds.), *Coastal wetlands zone '91 Conference-ASCE*, Long Beach, California, pp. 110-124.