

## Chapter 4: Coastal Impacts

Paul A. Montagna, Jorge Brenner, James Gibeaut, Sally Morehead

The Texas coast is likely to experience severe climate change impacts because of a synergy between the regional climate regime and the coastal geology. Lying between about 26° and 30° N latitude, the Texas coast is already in a relatively warm climate zone and subject to very high rates of evaporation (Larkin and Bomar 1983). Thus, potential changes in rainfall or temperature will have great impacts on the Texas coastal hydro-cycle. The Texas coastal plain is relatively flat and low-lying, and the Texas coast has one of the highest rates of subsidence in the world (Anderson 2005). Thus, changes in sea-level will be exacerbated on the Texas coast because the land is relatively flat and it is rapidly sinking. The combined effects of these changes can affect the physical and biological characteristics of the Texas coast dramatically.

In one of the earliest discussions of the potential impacts of climate change along the Texas coast, Longley (1995) focused on potential changes in habitat area that might result from changes in precipitation and concomitant changes in freshwater inflow to bays and estuaries. Other authors have focused on sea-level rise (Zimmerman et al. 1991) or temperature change (Applebaum et al. 2005). In addition, Twilley et al. (2001) provided a comprehensive assessment of climate drivers, such as changes in temperature, rainfall, freshwater resources, and sea-level rise, and the consequences of human activities as they act in concert with climate change effects.

If the Texas coast is indeed exceptionally susceptible to climate change effects, then there must be both physical and biological indicators of change. Temperature change itself, is an obvious indicator. Salinity is an indicator of changes in the fresh water cycle, because it dilutes sea water when it flows to the coast. It is also possible for indirect changes of water quality to occur because oxygen is less soluble in hotter, saltier water. Thus, the temporal dynamics of water quality change is also an indicator. Species that are sensitive to changes in any one or more of these physical factors, or reside at the edge of their distribution range are indicator species.

In the context of climate change, the indicator species are sensitive to either temperature, salinity, or elevation changes. One potential indicator species is the black mangrove (*Avicennia germinans*), because its distribution and survival in Texas is limited by winter temperature (Sherrod and McMillan 1981). Other indirect effects include explicit links between temperature and water quality and change in biotic responses. The earlier habitat change analysis conducted by Longley (1995) assumed only inflow rates will change, but rising sea levels may obliterate these effects. Therefore attention to effects of sea-level rise is critical. In the current study, focus is on identifying changes in the instrumental record (for both water and habitats) to determine if there are trends in recent long-term records of water temperature and quality, mangrove habitat cover, and sea level rise.

### TEXAS ESTUARIES

The Texas Gulf shoreline stretches 370 miles from the Sabine River at the Louisiana state line to the Rio Grande at the Mexican border. Except for two areas along the upper coast, narrow barrier islands and peninsulas separate the Gulf of Mexico from the shallow estuaries. Pritchard (1967, pp. 3–5) defines *estuary* as a semienclosed coastal

body of water that has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage. The estuaries behind the barrier islands and peninsulas project inland from the Gulf shoreline as much as 30 miles. The land surrounding these aquatic systems is low and flat; one must travel 30–50 miles inland from the Gulf shoreline to reach a land elevation of just 100 feet above mean sea level. The environments of the coastal region can be looked at from several scales of view: the region as a whole, individual estuaries, and habitats. Each viewpoint is useful in understanding the effects of climate and climate change upon estuaries.

## **River Basins**

The inland land areas from which runoff drains to rivers can be delineated on topographic maps through careful consideration of land elevation and slope. One or more river basins may drain to an estuary on the coast. The amount of fresh water that flows to an estuary has a strong influence on the shape and form of the estuary, as well as on the habitats and organisms there and in the surrounding wetlands. A regional viewpoint that considers the river basins of the entire state is illustrated in Figure 4.1, which shows the outlines of river basins that drain to the state's eleven estuaries.

Drainage basins for rivers that flow into the Brazos, Colorado, and Rio Grande estuaries extend across the entire state. Flows of water to these estuaries are influenced by rainfall and runoff from a large area, much of which is far removed from the coastline. The basin for the Rio Grande even extends into Mexico, New Mexico, and southern Colorado. Thus, climate changes occurring a long distance from Texas estuaries may nevertheless have a profound influence on the amount of fresh water that flows into them.

The Sabine-Neches, Trinity–San Jacinto, Guadalupe, and Nueces estuaries have smaller river basins that extend only partway across the state; the Sabine-Neches Estuary also receives some runoff from Louisiana. These smaller river basins are not directly affected by precipitation in the western half of the state. The San Bernard, Lavaca–Tres Palacios, Mission-Aransas, and Laguna Madre estuaries have the shortest river basins; they reach inland no more than about 100 miles from the Gulf shoreline. Runoff to these estuaries is most strongly influenced by the climatic conditions close to the coast.

The runoff rates vary by more than an order of magnitude between the basins bordering Louisiana and those bordering Mexico. Differences in runoff rates are the result of the interaction of the east-west precipitation (Figure 2.3) and evaporation gradients in the state, the north-east to south-west location of the basin along the coastline, and the distance the drainage basin extends inland from the Gulf shoreline. In general, the more a basin is restricted to the area near the coast, or the farther to the northeast it is located, the greater the average runoff per square mile. Basins that extend farther across the state or are located more to the southwest have lower rates of runoff.

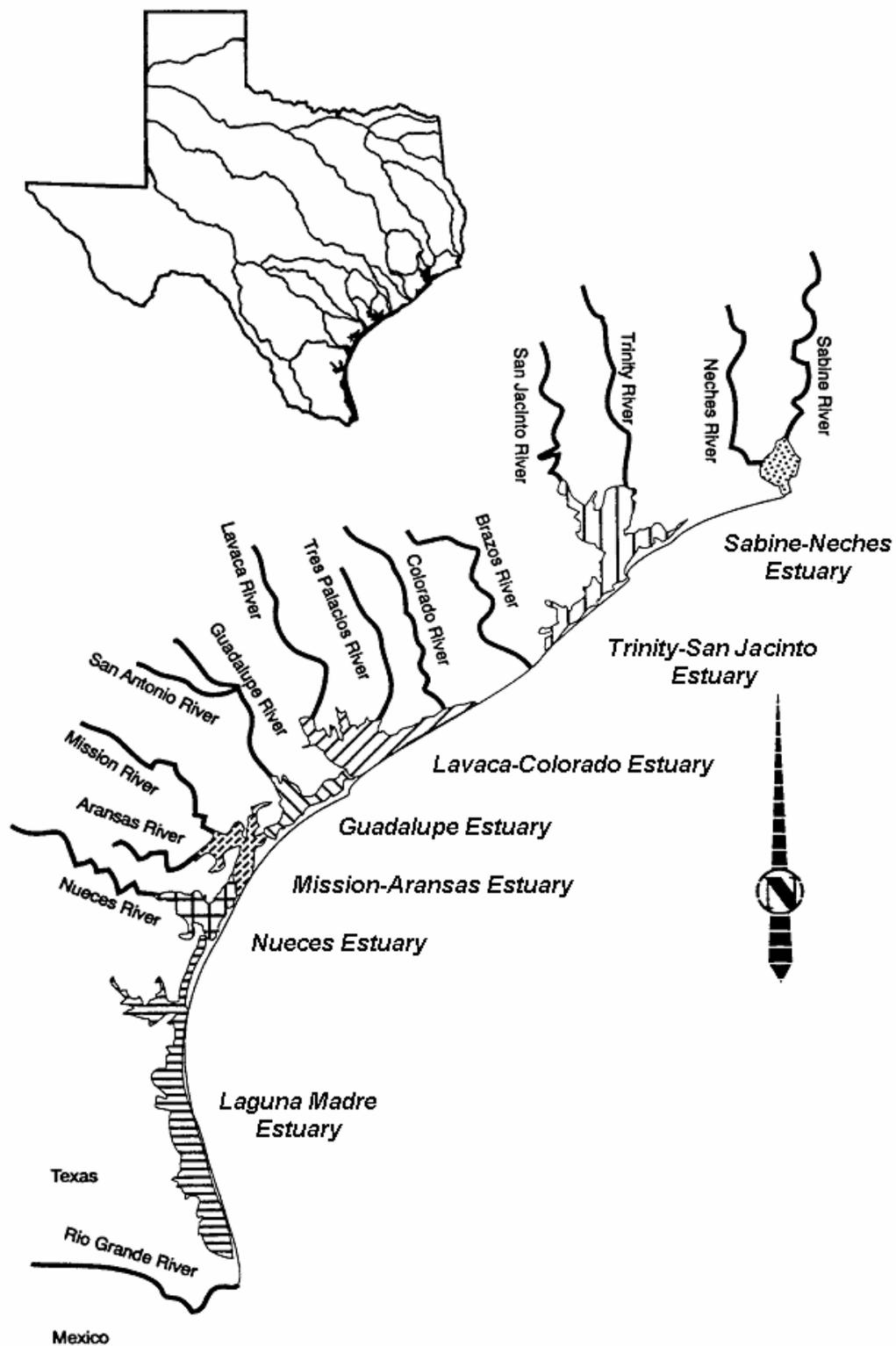


Figure 4.1. - Location of Texas Estuaries (Longley 1994).

### Estuary Forms and Climate

The development and configuration of estuaries on the Texas coast is closely bound to climatic changes that have taken place over the period from the last ice age to the present. Three major shapes or forms of estuaries can be seen in Figure 4.1, a medium-scale view of the Texas coast. The first is the classic estuarine configuration such as the Trinity–San Jacinto Estuary, which juts far inland and has an opening to the sea toward its southern tip. Rivers discharge at the most inland end of the estuary, and the axis between the river mouth and the openings to the sea allows the establishment of a long gradient of salinity ranging from low to high levels. Most of the land that surrounds this

estuary and others with the same physical form (Sabine-Neches, Lavaca–Tres Palacios, Guadalupe, Mission-Aransas, and Nueces) is of Pleistocene age (Fisher et al. 1972) and was formed 60,000–1 million years before present (B.P.). During the last ice age (Late Wisconsin glaciation), which began about 50,000–60,000 years B.P., sea level declined as water was captured in the ice sheets that covered part of the northern hemisphere. As sea level fell to its lowest point, 300–400 feet below its present level, the land where today's estuaries and near-shore gulf are located was completely exposed; surface sediment eroded, creating deep river valleys. Rivers flowed through these valleys at levels 100–130 feet lower than today's mean sea level. As the climate began to warm, about 20,000 years B.P., sea level started to rise and began to flood the river valleys. The deeper portions of the valleys gradually filled with sediment originating in upland runoff, offshore currents, and eroding valley walls. Offshore sediments that were transported onshore also contributed to the formation of barrier islands and peninsulas, which formed within the past 2,500 years. The processes of transport, deposition, and erosion have continued to the present, slowly filling the deeper areas of the estuaries and widening the edges of the Sabine-Neches, Trinity–San Jacinto, Lavaca–Tres Palacios, Guadalupe, Mission-Aransas, and Nueces estuaries.

River basins that drain to these classic-form estuaries are generally midsized or coastal basins and do not extend more than halfway across the state. The existence and shape of these estuaries is clearly a result of the climatic shift that occurred during the ice ages, the subsequent rise of sea level, and the transport and erosion of sediment affected by varying climatic conditions throughout the river basin area.

A second estuarine configuration is illustrated by the Brazos, Colorado and Rio Grande river mouths. The Brazos River and the Rio Grande now empty directly into the Gulf rather than into a bay. The Colorado River has recently been artificially diverted into the eastern portion of Matagorda Bay and no longer flows directly to the Gulf. During the last ice age, these rivers cut deep river valleys just like rivers flowing into the classic estuaries described above. As the climate warmed and sea level rose, however, these rivers carried so much sediment that their deltas expanded, completely filling their river valleys. This deposition continued all the way to today's Gulf shoreline, allowing the rivers to discharge directly into the sea. The great sediment load of these three rivers resulted from the large areas of their drainage basins, which extend across the entire state. The land immediately surrounding these estuaries was formed very recently; the rapid land growth and direct discharge into the Gulf of the river estuaries is the result of the interaction of climate, physiography, and soil type in the river basins over the past 5,000–10,000 years.

Initially, the San Bernard Estuary seems to be an exception to the generalization that the form of the river estuaries is the result of sedimentation in the large river basins that stretch across the state. Today the San Bernard Estuary has a very small basin, located between the present Brazos and Colorado river basins. The San Bernard River is most likely an abandoned channel of one or the other of these major rivers. When sea level approached its present level, about 2,800 B.P., the Colorado and Brazos rivers emptied into a common estuary and filled it in about 1,200 years (McGowen et al. 1976a). Because the present San Bernard River basin is entirely within the area affected by the Colorado and Brazos river sedimentation, this estuary and the land surrounding it were only recently formed by the large sediment loads of these two great river basins.

The third form of estuarine system on the Texas coast is the lagoon typified by the Laguna Madre. The water body is narrow, and the major axis runs parallel to the shoreline rather than perpendicular to it. Except for the area close to the Rio Grande, the land on the inland side of the lagoon was formed as fluvial-deltaic deposits or

strandplain during the Pleistocene (Brown et al. 1977; 1980). The barrier island side of the laguna was formed over the past 2,500 years, as sea level rose to its present position. Thus, even the current configuration of the Laguna Madre (which is actually two different systems: Upper Laguna Madre/Baffin Bay and Lower Laguna Madre) is the result of a rise in sea level as the climate returned to its present, interglacial state.

### **Changes in Shoreline**

Most of the sandy Gulf of Mexico shoreline of South Texas has probably been retreating for several thousand years and definitely since the mid to late 1800's when sufficiently accurate shoreline maps were constructed for comparison to today's maps. An analysis of multiple Gulf of Mexico shorelines from the 1930 to 2000 time period and from the Colorado River to the Rio Grande shows that 56 percent of the shoreline retreated at a mean rate of 2.2 m/y (7.2 feet/y), 36 percent was essentially stable, and only 8 percent advanced seaward. The advancing shoreline sections were associated with impoundment of sand by jetties or spit progradation caused by engineering alterations affecting Pass Cavallo. A section a few miles long in the central Padre Island area also advanced because of the natural convergence of littoral drift.

Bay shorelines have been retreating for at least 10,000 years as sea-level rose from the lowstand of 18,000 years ago and flooded paleo river channels running through the bays. Inundation, waves, and tidal action eroded the river banks, and the resulting shoreline retreat largely shaped the bays as they exist today. Generally, these bay shorelines continue to retreat with the erosion of marshes and flats, clay bluffs, sandy slopes, and sand and shell beaches. In some areas, extensive shore protection structures such as rip rap and bulkheads have been installed. Paine and Morton (1993) determined an average retreat rate for the Copano, Aransas, and Redfish bay systems of 24 cm/y (0.8 feet/y) from 1930 to 1982. In Baffin Bay, most of the shoreline retreated from 1941 to 1995 (Gibeaut and Tremblay 2003).

## **EFFECTS OF CLIMATE CHANGE ON COASTAL REGIONS**

### **Sea-Level Change**

Changing sea level relative to the land (relative sea-level change) and the increase and decrease in sand supply to the coast causes shorelines to retreat or advance over a period of 100 years or more (Bruun 1962; Gibeaut and Tremblay 2003). The rise in relative sea level during the last 100 years along the Texas coast has moved the Gulf and bay shorelines through inundation and by shifting the erosive energy of waves and currents landward. This has happened because, overall, the rate of new sediment delivered to the littoral zone has not been sufficient to stem the effects of relative sea-level rise.

Localized exceptions to this are where rivers form deltas at the heads of the bays, such as the Nueces and Mission deltas, and where creeks erode bluffs and enter the bays (Morton and Paine 1984; Paine and Morton 1993) and where dunes have migrated and advanced the shoreline (Gibeaut and Tremblay 2003, Prouty and Prouty 1989).

Because of this sediment deficit and the low-lying and gently sloping shores of much of the South Texas coast, relative sea-level rise has had and will continue to have a profound effect on coastal habitats. Increases in the rate of global sea-level rise, as projected by global climate modeling (Intergovernmental Panel on Climate Change - IPCC- (2007), and coastal development will very likely result in further decreases of coastal wetland habitats.

Relative sea-level rise along the South Texas coast is caused by natural and man-induced land surface subsidence and a “global” rise in ocean level. Global sea level is rising primarily through the addition of water to the oceans by melting continental ice and, to a lesser degree, through thermal expansion of ocean water (Miller and Douglas 2004), both of which are caused by global warming. Tide gauge records in south Texas, which include the effects of land subsidence, show that relative sea level has risen at a rate of 4.6 mm/y (0.18 inches/y) at Rockport (since 1948), 2.05 mm/y (0.08 inches/yr) at Port Mansfield (since 1963), and 3.44 mm/y (0.14 inches/y) at South Padre Island (since 1958) (Zervas 2001). Douglas (1991) considered tide gauges from around the world and, after accounting for vertical land movements, determined that global sea level from the late 19th to the late 20th century rose at a rate of only 1.8 mm/y (0.07 inches/y). Land subsidence rates can be estimated for the tide gauge locations by subtracting 1.8 mm/y (0.07 inches/y) from the relative sea-level rise rate recorded by the gauge. This illustrates that land subsidence is an important component of relative sea-level rise along the Texas coast.

Additional land subsidence is caused by groundwater withdrawal and oil and gas production which decreases pore pressures in underlying sediments allowing further compaction. Ratzlaff (1980) compared releveling surveys for various periods from 1917 to 1975 and observed locally high land subsidence rates of as much as 49 mm/y (1.93 inches/y) such as at the Saxet oil and gas field southwest of Nueces Bay. The highest rates correlated with oil and gas and groundwater production. By combining tide gauge and releveling data, Paine (1993) estimated Texas coastal subsidence rates of 3 to 7 mm/y (0.12 to 0.28 inches/y). Sharp et al. (1991) and Paine (1993) hypothesized that regional depressurization of petroleum reservoirs were the cause of historical subsidence rates being much higher than the geologically long-term rates. Morton et al. (2006) provided evidence of hydrocarbon production causing regional land subsidence and associated wetland loss in the Mississippi Delta and the upper Texas coast regions.

The IPCC (2007) report provides model projections for global sea-level rise based on six greenhouse gas and aerosol emission scenarios. The range in the amount of projected global sea-level rise by 2099 relative to the average from 1980 to 1999 is 0.18 to 0.59 m (0.6 to 1.9 feet). After adding estimates for local land subsidence, the amount of projected relative sea-level rise by the year 2100 is 0.46 to 0.87 m (1.5 – 3 feet) at Rockport, 0.2 to 0.61 m (0.66 - 2 feet) at Port Mansfield, and 0.34 to 0.75 m (1.1 - 2.5 feet) at South Padre Island. These amounts will likely be greater in areas with relatively thick Holocene deposits filling paleo river channels and tidal inlets such as along the barrier islands and modern deltas at the heads of the bays (e.g., Nueces River Delta), and they may be much higher where subsidence caused by groundwater and hydrocarbon extraction occurs.

Depositional subenvironments of barrier islands and bay margins are the substrates for various types of aquatic, wetland, and upland habitats. These subenvironments and associated habitats are closely linked to elevation relative to sea level through the processes that form and maintain them. On the low-lying, sandy barrier islands of the micro tidal (tide range 0.6 m or two feet on the open coast and less than 0.3 m or one foot in the bays) Texas coast, a rise of just 0.1 m (0.3 feet) in relative sea level can cause conversion of fringing low marshes and flats to open water and sea grass beds, and usually dry high marshes and flats to usually wet low marshes and flats (Gibeaut et al. 2003).

Mustang Island is a barrier island at the mouth of Corpus Christi Bay (Figure 4.2). Most of the island, except for the tallest foredunes, is less than 3 m (10 feet) above sea level, which is typical for the barrier islands along the south Texas coast.

Inundation of Mustang Island by the relative sea-level rise amounts projected for 2100 are depicted in Figure 4.3. Even a rise of just 0.46 m (1.5 feet) will cause lateral shifts of 1 to 2 km (0.6 – 1.2 miles) of the bay-side wetland environments. The upper bound rise amount of three feet will narrow the upland areas of the island to a width less than 200 m (656 feet) in places and flood central portions of the City of Port Aransas on the north end of the island.

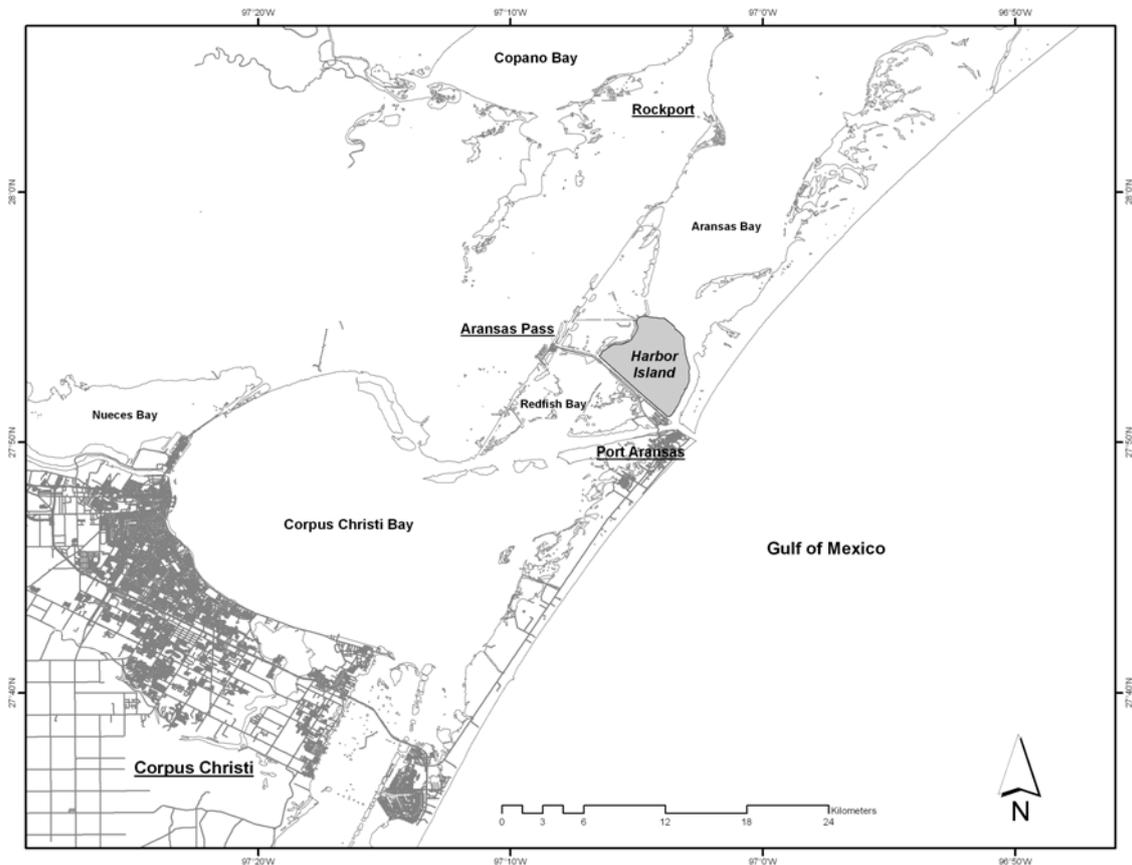


Figure 4.2. Location of Harbor Island in the Texas coast.

Actual shoreline retreat and loss of wetland areas on Texas barrier islands will depend not just on relative sea-level rise but also on (1) if vertical sediment accretion can keep up with the rise, (2) if adjacent upland slopes are gentle enough for wetlands to migrate landward, (3) if development obstructs the upward/landward migration of wetlands, and (4) the severity of the erosion of the edge of the marshes and flats by waves and currents. Based on the observed conversion of tidal flats to open water and sea grass beds and the migration of marshes into higher areas since the 1950's on Mustang and adjacent islands (White et al. 2006), it is unlikely that vertical accretion will offset the effects of an increase in the rate of relative sea-level rise. Upland slopes increase toward the core of the islands, which will temper the amount of new marsh that can develop, and it is very likely that future development will obstruct new marsh creation, such as occurred at the Padre Isles development beginning in the 1970's (Figure 4.3) (White et al. 2006). Erosion of the outer edges of marshes and flats since the 1930's has caused shoreline retreat in the range of 0.5 to 2.5 m/yr (1.6 - to 8 feet/yr) along most of the Mustang Island bay shoreline (Morton and Paine 1984; Williams

1999). Erosion by waves may increase as higher water level decreases the amount of wave shoaling and extends wave energy farther landward.

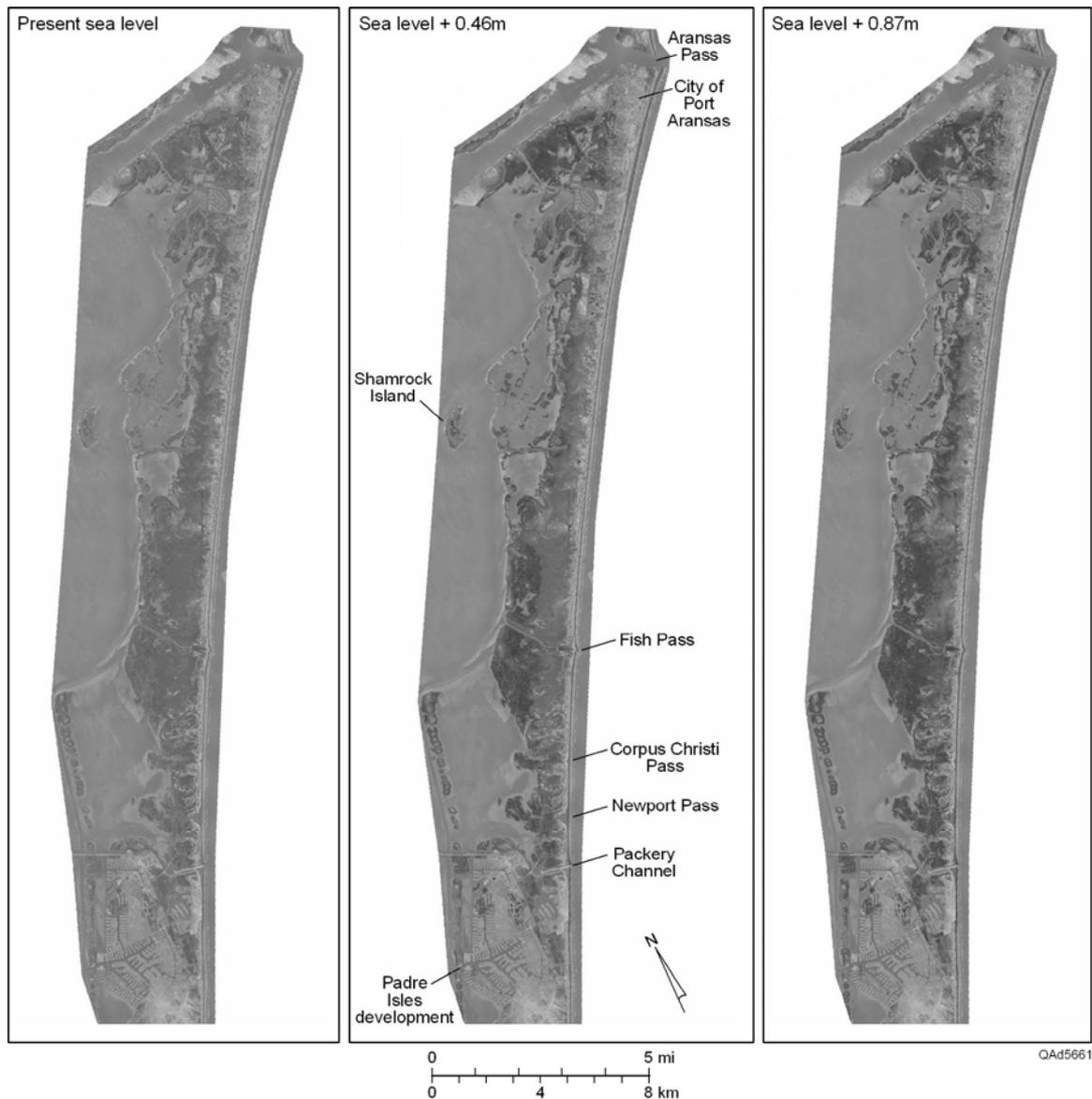


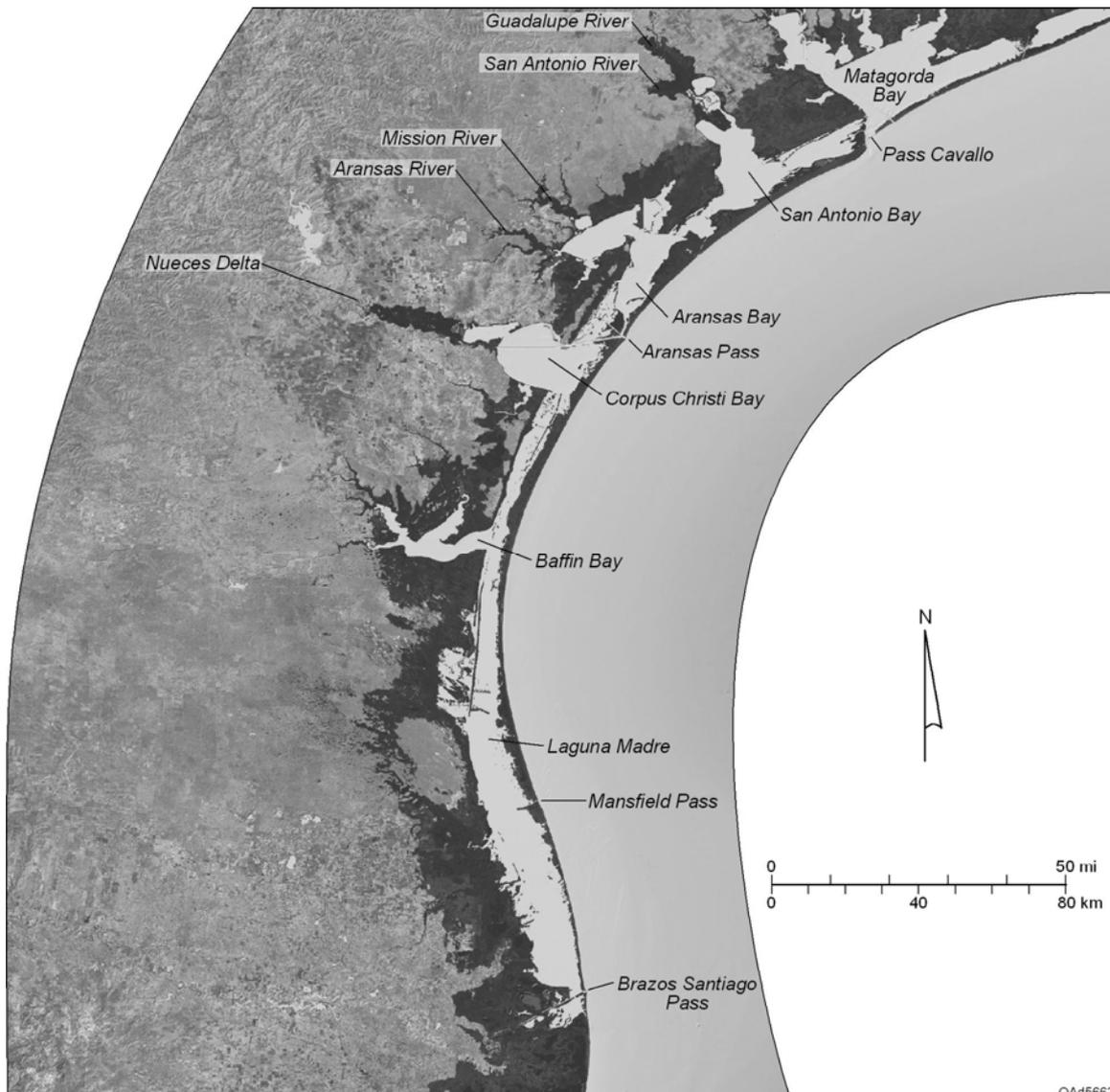
Figure 4.3. Inundation of Mustang Island. The amounts of sea-level rise depicted here are expected in 100 years when combining local subsidence estimates with the lower and upper ranges of global sea-level rise projections presented in the IPCC (2007) report. This map was created using aerial photography draped on a high-resolution, lidar-derived digital elevation model. Lidar data acquisition and processing were performed by the Bureau of Economic Geology, The University of Texas at Austin in 2005.

As sea-level rises and the barrier islands become narrower, large storms will eventually breach, wash-over, and transport sand landward into the bays. This process is already happening along low and narrow portions of the South Texas coast such as Corpus Christi and Newport Passes during Hurricane Beulah in 1967 (Davis Jr. et al. 1973) (Figure 4.3). Furthermore, increasing aridity, which climate models predict for this region, has the potential to reduce stabilizing dune vegetation and cause more active dune migration and blow outs as were observed on north Padre and Mustang Islands

during the drought period of the 1950's (Prouty and Prouty 1989; White et al. 1978). Hurricane intensities have increased recently and may continue to increase with warming sea-surface temperatures (Emanuel 2005). Hence, rising sea level, increasing aridity, and increasing storm intensity will drive the Texas barrier islands toward narrower, lower-lying islands that are more frequently washed over and severed by tropical storms. Texas (Eventually, depending on the actual rate of relative sea-level rise, portions of the Texas barrier island chain will be destroyed, similar to the near demise of the Chandeleur Islands in Louisiana following recent hurricanes.

The IPCC (2007) climate projections for global sea-level rise discussed previously do not include the full effects of potential changes in polar ice sheet flow as global warming proceeds. Recent observations of ice sheet changes suggest the possibility of large contributions to sea-level rise from the flow of Greenland and Antarctic glaciers into the oceans (Rignot and Kanagaratnam, 2006; Shepherd and Wingham, 2007). Overpeck et al. (2006) compared 100-year global temperature projections in the IPCC Third Assessment Report (2001) with climatic and sea level conditions during the last interglacial period about 130,000 years ago. During that time, polar temperatures were 3 to 5 °C (5.4 – 9°F) higher than now causing polar ice to retreat and contribute to sea level 4 m (13 feet) to more than 6 m (20 feet) higher than today. This amount of warming is within the range projected during the next 100 years by IPCC modeling studies. Increases in sea level caused by melting polar ice, therefore, may be expected to proceed for centuries resulting in sea-level rise of several meters and sea-level rise rates twice those projected in the IPCC (2007) report (Overpeck et al. 2006).

Figure 4.4 depicts inundation of the Texas coast if sea-level were to rise 6 m (20 feet). In this scenario, the barrier islands are completely inundated, and the sea advances about 20 km (12.5 miles) inland from the bay margins except where sufficiently high Pleistocene bluffs and uplands exist. River valleys and deltas at the heads of the secondary bays are flooded. White et al. (2002) showed that vertical accretion rates on the Nueces Delta are less than the rate of relative sea-level rise today. It is unlikely that vertical accretion rates will be sufficient to maintain wetlands on the south Texas deltas when relative sea-level rise rates are 10 mm/y (0.4 inches/y) or more, as would happen in the Figure 4.4 scenario. If polar ice sheet destabilization should occur, therefore, we can expect massive losses of critical wetland habitat in the bays.



QAd5663

Figure 4.4. Inundation of land if the level of the sea were to rise 20 feet above present level. Lighter grey shows the present bays and lagoons and the darker grey depicts inundated areas. This scenario is reflective of polar ice sheet melting and destabilization triggered by global warming during the next 100 years. Constant redistribution of sediments by waves and currents during sea-level rise would tend to smooth the shoreline, but that process is not reflected in this map.

## Water Quality

Water quality data was obtained from the newly published Texas Water Data Services (<http://data.crwr.utexas.edu/>). The water quality data originates from the Coastal Fisheries Division of the Texas Parks and Wildlife Department (TPWD). The TPWD samples all Texas bays monthly using a probabilistic sampling design, i.e., stations within bays are randomly sampled. The TPWD collects organisms at trawl stations in the bays and simultaneously collects water data using multiparameter sondes to measure salinity, temperature, and dissolved oxygen, which are measured at one foot from the bottom.

Texas follows the traditional system of naming an estuary for the river(s) that dilute sea water (Longley 1994). In NOAA publications (e.g., Orlando et al. 1993), these systems are named after the primary bay (Sabine Lake, Galveston Bay, Matagorda Bay, San Antonio Bay, Aransas Bay, Corpus Christi Bay, and Laguna Madre, respectively). In addition, TPWD samples in the Gulf of Mexico, making a total of eight marine systems measured.

A total of 173,735 water quality observations have been made between 1976 and 2007. Because the number of samples varies among bay-month combinations, the first step in data reduction was to calculate means by bay-month combination. Then the data was averaged by year to analyze for year-to-year differences among bays and the Gulf of Mexico.

An analysis of covariance (ANCOVA) was used to analyze the water quality data, because the data was reduced to one annual sample taken in each bay system. Thus, regions are blocks, and year is the covariate. The year\*bay system interaction was used to test for common responses among regions (called a test for heteroscedasticity). All data management, data aggregation, reduction, and ANCOVA were conducted using SAS 9.1 software (SAS Institute, Inc., 2004, 2006).

There is a climatic gradient along the Texas coast, which influences freshwater inflow to estuaries. The gradient of decreasing rainfall, and concomitant freshwater inflow, from northeast to southwest, is the most distinctive feature of the coastline. Along this gradient, rainfall decreases by a factor of two from 142 cm/y (56 inches/y) near the Louisiana border to 69 cm/y (27 inches/y) near the border with Mexico (Larkin and Bomar, 1983). Inflow balance however, decreases by almost two orders of magnitude from about 17 billion m<sup>3</sup>/y in Sabine Lake to about -900 billion m<sup>3</sup>/y in Laguna Madre (Longley 1994). Inflow balance is the sum of freshwater inputs (gauged, modeled runoff, direct precipitation, plus return flows) minus the outputs (diversions and evaporation). The net effect is an increase in salinity as we move down the Texas coast from the Louisiana border. The average salinity in Sabine Lake is 7 parts per thousand (ppt) as compared with 36 ppt in Upper Laguna Madre (Table 4.1), a hypersaline lagoon (the nearshore Gulf of Mexico averages 31 ppt).

Table 4.1. Annual water quality parameters (mean and standard deviation in parentheses) for bay systems over the period 1976 – 2007 (i.e., n = 32).

Bay System	Salinity (ppt)		Temperature (°C)		Dissolved Oxygen (mg/L)		Turbidity (NTU)	
Gulf of Mexico	30.52	(1.16)	22.19	(0.55)	7.09	(0.56)	11.88	(5.13)
Sabine	7.07	(2.83)	21.92	(1.05)	8.08	(1.02)	25.93	(6.03)
Matagorda	19.98	(4.58)	22.67	(0.75)	7.98	(1.03)	35.12	(13.49)
Galveston	16.03	(3.18)	22.23	(0.68)	8.28	(0.98)	38.53	(24.52)
San Antonio	16.81	(4.90)	22.82	(0.64)	7.99	(0.87)	29.40	(10.77)
Aransas	18.40	(5.59)	22.93	(0.78)	8.25	(0.73)	30.86	(16.74)
Corpus Christi	28.99	(3.78)	23.22	(0.81)	7.59	(0.72)	29.77	(24.44)
Upper Laguna Madre	35.94	(7.00)	24.07	(1.00)	7.22	(0.67)	36.08	(25.63)
Lower Laguna Madre	32.07	(2.74)	24.36	(1.01)	7.82	(0.71)	35.05	(23.92)

There has been a long-term trend of increasing temperature along the entire coast (Figure 4.5). The patterns over time are different among the different systems. The main difference is a higher rate of increase in Lower and Upper Laguna Madre than

in the other seven ecosystems. The overall average rate of increase in temperature is  $0.0428\text{ }^{\circ}\text{C}/\text{y}$ , which translates into an increase of  $1\text{ }^{\circ}\text{C}$  in 23 years ( $1\text{ }^{\circ}\text{F}$  in 13 years).

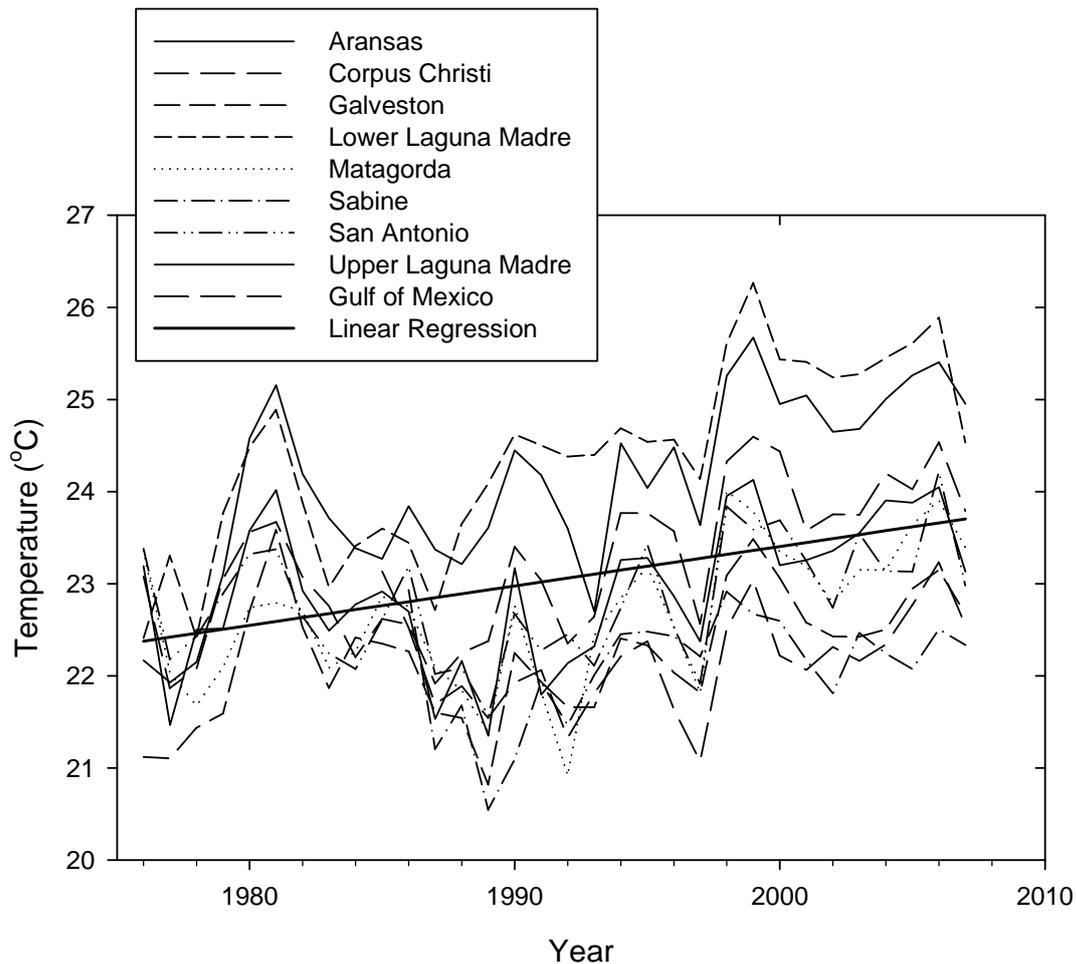


Figure 4.5. Average annual water temperature in Texas coastal ecosystems.

In contrast, there has been a long-term trend of decreasing dissolved oxygen along the entire coast (Figure 4.6). The patterns over time are different among the different systems. The main difference is a higher rate of decrease in Galveston Bay and Upper Laguna Madre than in the other seven ecosystems. The overall average rate of decrease in dissolved oxygen is  $0.0532\text{ mg/L/y}$ , which translates into an increase of approximately 0.7 percent per year.

Salinity patterns are similar among all the ecosystems ( $P = 0.6470$ ), but there are differences in salinity among the regions ( $P = 0.0001$ , Table 4.1). The differences in salinity are related to the climatic gradient along the Texas coast as described earlier. There is no evidence of salinity change over time ( $P = 0.5464$ ).

The increase of temperature and decrease of dissolved oxygen was noted previously in just Corpus Christi Bay, Texas (Applebaum et al. 2005). Both rates for the period 1982 to 2002 were greater than reported here for 1976 to 2007. The initial report was for temperature increasing at a rate of  $0.07\text{ }^{\circ}\text{C}/\text{y}$  and dissolved oxygen decreasing at a rate of  $0.06\text{ mg/L/y}$ . The fact that this joint observation is occurring everywhere in Texas indicates the general nature of the indirect effects of air temperature increases. The relationship between temperature and dissolved oxygen is causal because oxygen solubility in water decreases with increasing temperature. It

appears that increased sea temperatures will lead to decreased dissolved oxygen and water quality in many places of the world. This may, in part, explain the increasing number of hypoxic zones worldwide (Diaz and Rosenberg 2008).

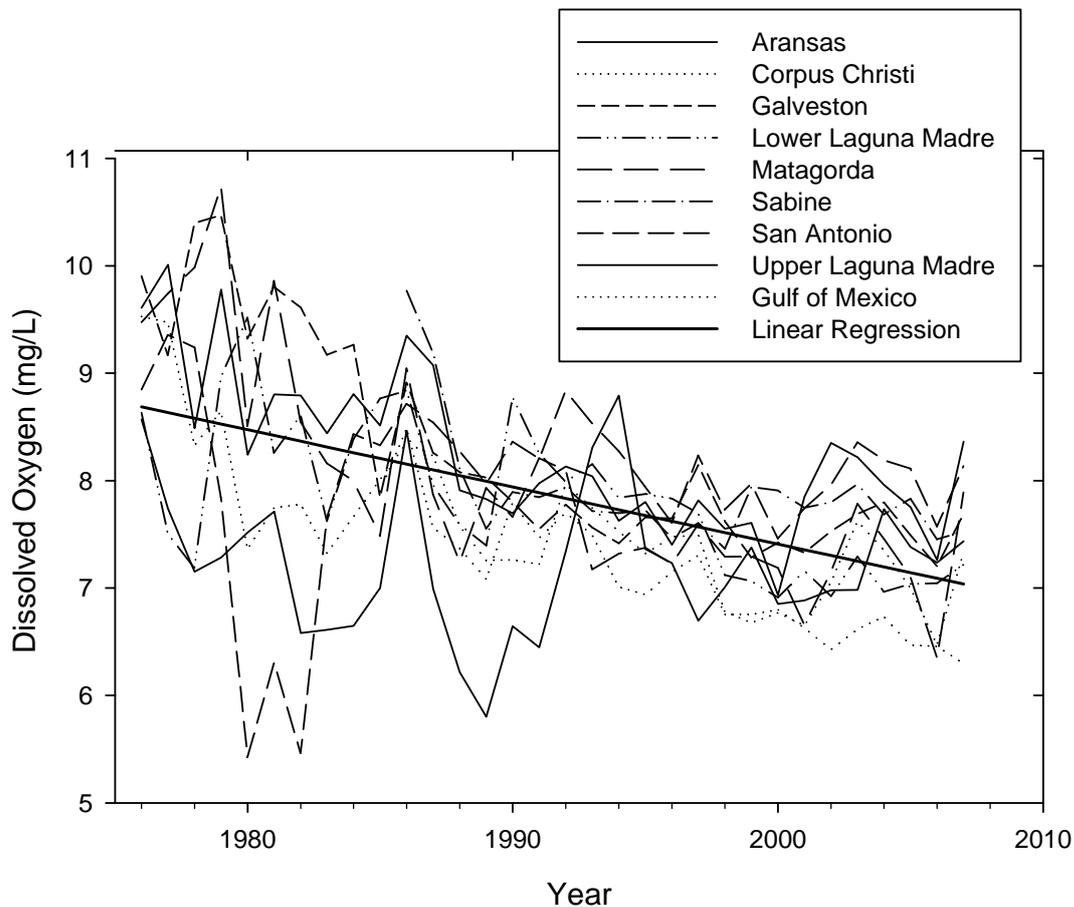


Figure 4.6. Average annual dissolved oxygen concentrations in Texas coastal ecosystems.

As found earlier by Applebaum et al. (2005), there was no trend in salinity with time in the current coast-wide analysis. The importance of global scale climate events driving regional-scale climatic variability and salinity structure in Texas estuaries is now reasonably well understood (Tolan 2007). The El Niño-Southern Oscillation (ENSO) index is correlated to salinity structure within Texas estuaries within 4 to 6 months. During ENSO events, salinities in Texas estuaries decrease because of increased rainfall and freshwater flows to the coasts. During La Niña periods, salinities increase because of the drier climatic conditions. These cycles occur with a periodicity of 3.55, 5.33, and 10.67 years. The ENSO is dominated by the 3.55- and 5.33-year periods and the 10.67-year period is defined by the Pacific Decadal Oscillation. The link with ENSO explains the year-to-year variability in salinity along the Texas coast.

Other evidence indicates that there are long-term trends of lower rainfall in the Gulf of Mexico and the US Southwest. With increased temperatures and decreased rainfall, a water deficit would be expected where evaporation exceeded rainfall. These are the same conditions that cause hypersalinity in Laguna Madre. During the period between 1987 and 2006, the Gulf of Mexico had a strong water deficit, as did most of the Pacific Ocean between about 15 and 30 °N latitude (Wentz et al. 2007). Between

about 1975 and 2007, the American Southwest suffered a water deficit in general (Seager et al. 2007). With this strong evidence of regional water deficits, it is surprising that there is no long-term trend of increasing salinities. It is possible that the trend is masked by smaller scale oscillations, or that extreme events are more common and droughts are simply followed by floods, and the long-term mean of the water balance is less important than the variance of the water balance.

Increasing sea surface temperatures along the Texas coast mimic what is occurring in many of the World's oceans. These increased surface temperatures are correlated to increased occurrence of intense tropical storms (Webster et al. 2005). Tropical storm activity is variable from year to year, but more intense storms could have dramatic effects on coastal inundation and habitats.

### **Distribution of Mangroves**

Mangroves are littoral plants that occur in tropical and sub tropical coasts worldwide. These woody plants grow at the interface between land and sea where they exist in conditions of high salinity, extreme tides, strong winds, high temperatures and muddy, anaerobic soils (Kathiresan and Bingham 2001). There may be no other group of plants with such highly developed morphological and physiological adaptations to extreme conditions.

Mangrove habitats are among the world's richest repositories of biological diversity and primary productivity (Tomlinson 1986). Mangroves help maintain genetically diverse coastal fauna and flora that are of social-ecological value to humans throughout the world. They constitute an important source of benefits for humans by serving as coastal protection, habitat for other terrestrial and marine species, and nursery for important commercial fisheries including fish, mollusks and crustaceans. In developing countries mangrove forests constitute an important source of fuel, raw materials for construction and food.

With more than 50 percent of the people living near the coast, mangroves constitute a critical element of the coastal environment. The main drivers of change in mangrove communities are competition for land for aquaculture, agriculture, infrastructure and tourism. Some 15.2 million ha of mangroves were estimated to exist worldwide in 2005, down from 18.8 million ha in 1980 (FAO 2007). Due to the drastic loss observed around the world their conservation is crucial not only for the biodiversity and human societies that depend on mangroves but for the survival of coral reefs and seagrass beds (Spalding et al. 2009).

Six species of mangrove are reported to occur in the United States: *Rhizophora mangle*, *Laguncularia racemosa*, *Avicennia germinans*, *Conocarpus erectus*, *Avicennia schaueriana*, and *Acrostichum aureum* (FAO 2007). Most recent estimates indicate that there were 197,648 ha of mangroves in 2001 in the United States. Together, the United States, Panama, and Bahamas account for 82 percent of total mangrove area in North and Central America. However, the second largest documented rate of loss in North and Central America was recorded in the United States. Over the past three decades mangrove forests have experienced reductions of 1.3 percent from 1980 to 1990, -0.8 percent from 1990 to 2000, and -0.5 percent from 2000 to 2005 (FAO 2007).

Although mangroves are now under higher protection in areas such as the Everglades National Park in Florida, they are still being damaged mainly by drainage for agriculture, reclamation for urban development, and canalization in the United States. At a regional scale, hurricanes represent a serious threat to mangroves and cause significant losses in the United States (FAO 2007).

Four species of mangroves occur in the Gulf of Mexico: red mangrove (*Rhizophora mangle*), white mangrove (*Laguncularia racemosa*), black mangrove (*Avicennia germinans*) and button mangrove (*Conocarpus erectus*) (Sherrod and McMillan 1985). Among those, only black mangrove occurs in Texas, west of Apalachicola Bay, Florida, and north to the Rio La Pesca, Tamaulipas, Mexico (Lot-Helgueras *et al.* 1975). Galveston Island is the historical northern limit of black mangroves (Sherrod and McMillan 1981), but mangroves appear to be establishing themselves more firmly on the Louisiana coast (Twilley *et al.* 2001). Temperature, salinity and several other environmental factors limit the distribution and survival of black mangrove in Texas. Black mangrove is the only species known to be tolerant to winters in Texas (Sherrod and McMillan 1981, Tunnell 2002). In Texas, mangroves are recognized as the only conspicuous native woody vegetation of the marsh-barrier island ecosystem (Judd 2002), and are sparsely distributed along tidal channels in bays and estuaries (Pulich and Scalan 1987, Withers 2002). This species rarely exceeds six feet in height, and is most commonly distributed in the southern coast of Texas (Tunnell 2002).

## Black Mangroves

Black mangroves have been impacted mainly by environmental and climatic fluctuations as well as anthropogenic modifications in Texas. Although human activity has resulted in the decrease of mangroves, it has also been responsible for the increase of intertidal marsh habitat within this past century because of coastal dredging and channelization (Pulich *et al.* 1997, Tremblay *et al.* 2008). However, different climatic periods appear to have had a large influence on mangrove population fluctuations during the past two centuries in the Texas coast (Sherrod and McMillan 1985).

On the Texas coast, there are four primary populations of black mangroves: Port Isabel (Cameron County), Harbor Island (Aransas Pass; Nueces and Aransas Counties), Port O'Connor (Cavallo Pass; Calhoun County), and Galveston Island (Galveston County) (Sherrod and McMillan 1981).

Harbor Island contains one of the densest and largest populations of black mangroves documented since 1930s on the Texas coast (Britton and Morton 1989). Harbor Island is a flood-tidal delta located at the mouth of Aransas Pass inlet, which separates Mustang Island and San Jose Island (Figure 4.2). Harbor Island also borders two bays, Aransas Bay to the north and Redfish Bay to the south. It is bounded by the Lydia Ann Channel that connects the Intra Coastal Water Way between Aransas Pass and Port Aransas. This tidal delta complex represents the most extensive and northernmost estuarine tropical wetland on the Texas coast (Pulich 2007).

Black mangroves are a good indicator for climate change because they occur in monospecific stands, are intertidal, and are at their northern limit for temperature on the Texas coast. The objective of the present study was to analyze the change in spatial cover over time of the population of black mangrove in Harbor Island, Texas and linkages with recent climate change patterns.

The change of spatial coverage of black mangrove in Harbor Island was analyzed by comparing past mapping efforts. A spatial information system was developed by digitalizing available historical paper maps, photo interpretation of digital aerial photographs, and integrating geographic information systems (GIS) layers for four years: 1930, 1979, 1995 and 2004. Data description and sources:

- 1930: Method: visual interpretation of aerial photograph. Digitized from picture negative. Source: Sherrod 1980.
- 1979: Method: visual interpretation of aerial photograph. Digitized from picture negative. Source: Sherrod 1980.
- 1995: Method: visual interpretation of digital Ortho Quarterquads (DOQQs) of color infrared photography. Horizontal resolution = 1×1 m. Source: US Geological Survey.
- 2004: Method: Image segmentation was performed using the blue, green, red, and near-infrared bands for each of the six processing areas. Classification of the habitat segments (as ESRI™ Shapefile file format) was performed using CART analysis by Coastal Services Center-National Oceanic and Atmospheric Administration (and consultant: TerraSurv, Inc. of Pittsburgh, PA) of color aerial photograph (digital multi-spectral imagery: ADS-40), scale 1:2,000, data ground truthed: May, June, and July 2006 and January 2007. Horizontal resolution = 2×2 m. Source: National Agricultural Imagery Program (NAIP)-US.

Methods used in previous studies to determine mangrove abundance using aerial photography along the Texas coast were followed (Sherrod and McMillan 1981, Everitt and Judd 1989). Four individual maps, corresponding to each year analyzed, were compiled using polygons in Shapefile (vector model) in ArcGIS v9.2 (ESRI™) GIS software. Layers were georeferenced to Universal Transverse Mercator (UTM zone 16) system and the NAD83 Datum to allow spatial overlapping and comparisons. Maps of the mangrove expansion of each year were created using the same cartographic scale for comparison purposes.

The spatial coverage of black mangrove in Harbor Island during the four periods analyzed changed (Figure 4.7). The cover area of black mangrove was calculated by summing the individual mangrove polygons (10.4 ha each) in Harbor Island using GIS (Table 4.2). There was a total increase in cover area of 131 percent over the 74-year period analyzed. The increase in area however, was not linear during the period. There was a decrease in mangrove area cover of 47.16 percent between 1979 and 1995 in Harbor Island. The areal extent recovered by 2004, and was greater than the previous extent in 1979.

The decrease of mangrove cover in Harbor Island observed between 1979 and 1995 could be linked to the four consecutive years of freezes (i.e., the number of days with a minimum temperature below 32 °F) that the Corpus Christi area experienced in 1982 (10 days), 1983 (13 days), 1985 (14 days) and 1989 (16 days) (Figure 4.8). Mortalities of 85 percent of black mangrove have been reported in 1984 due to the freeze in 1983 (Sherrod and McMillan 1985). There were 11 years between 1940 and 1997 with more than 10 days below freezing in Corpus Christi area. Accordingly, 81 percent of the freezes of 10 days or more together with the largest number of days (from 12 to 17 days) occurred since 1963.

Table 4.2. Black mangrove cover in Harbor Island, Texas during four study periods.

<b>Year</b>	<b>Area (ha)</b>
1930	235.54
1979	548.29
1995	372.56
2004	545.58

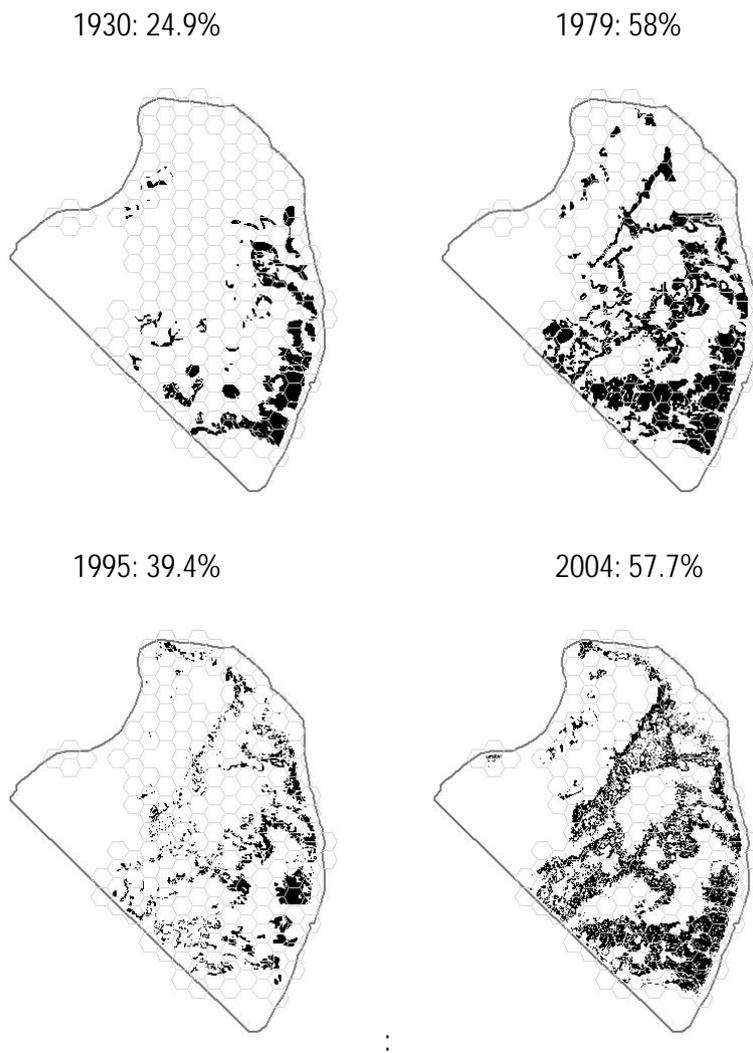


Figure 4.7. Area covered by year of black mangrove in Harbor Island, Texas. Values at the top represent percentages of maximum combined historical coverage up to 2004. Hexagons represent maximum combined historical extent up to 2004. Outer boundary represents Harbor Island limits in 2004.

The distribution pattern indicates that mangroves have occurred in most of the total area, but especially in the southeastern portion. The total cover in the Harbor Island area, extrapolated from the study area, is 2,484.43 ha in 2004.

Although a small increase in air temperature may have little direct effect on mangrove physiology, it is expected to cause a northern shift in the freeze line and consequently a northern shift in the distribution of mangroves (Field 1995, Twilley et al. 2001). Black mangroves appear to be more firmly established on the Louisiana coast (Twilley et al. 2001). Results presented here show an increase in mangrove distribution along the south-central Texas coast.

Mangroves represent a well-defined niche in coastal zonation and therefore are likely to be early indicators of the effects of global climate change. Warmer temperatures, as predicted by the United Nations Intergovernmental Panel on Climate Change (IPCC 2007), will facilitate the expansion of tropical species northward, such as mangroves (Montagna et al. 2007). However, black mangroves are typically found in sheltered coasts of the intertidal fringe, and as such are sensitive to temperature and

inundation. Thus, climate change has other implications for mangrove populations, and these include an increase in sea-level, a change in the number of days below freezing temperatures, and in the frequency and intensity of hurricanes striking. These changes are expected to have a greater impact in the Texas coast (Field 1995, Sherrod and McMillan 1985, Montagna *et al.* 2007, Ning *et al.* 2003, Tremblay *et al.* 2008).

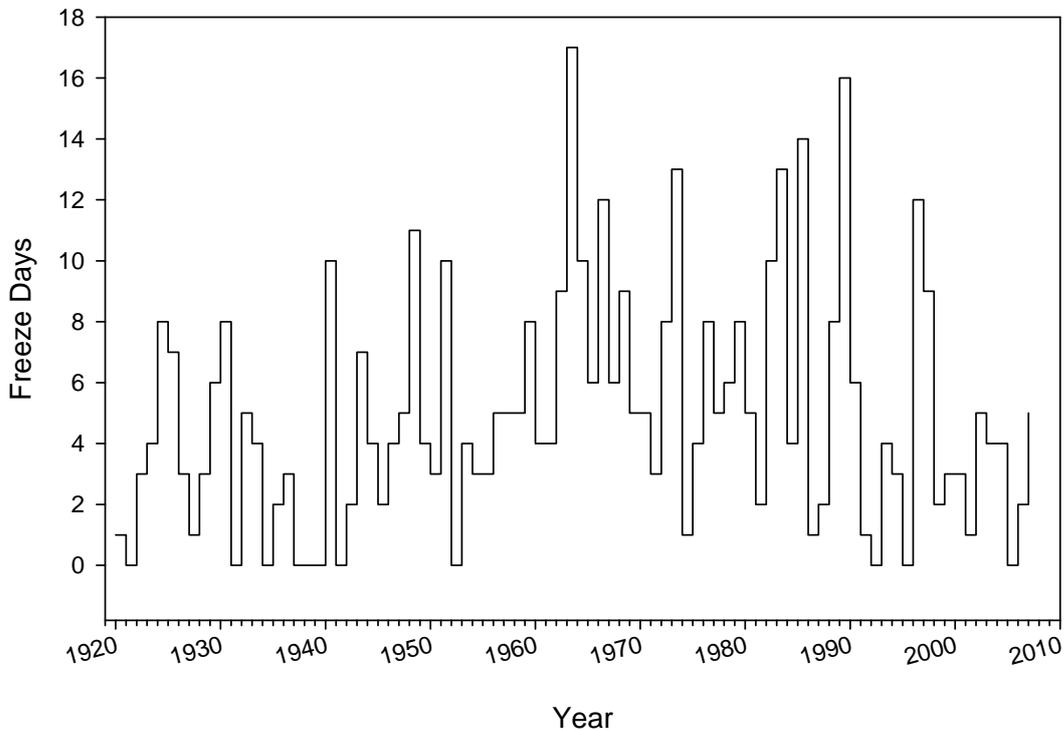


Figure 4.8. Number of days with minimum temperature below 0°C (32°F) (1920 - 2007). Data source: Corpus Christi Int. Airport, Texas; Station COOP ID # 412015 - NCDC/NOAA.

In Texas, black mangrove is at the northern limit of its range and thus catastrophic mortality due to freezes may occur. Although McMillan (1975) suggested that the Texas population belongs to a genetic race capable of surviving colder temperatures, the December 1983 freeze resulted in an 85 percent reduction in Texas (Sherrod and McMillan 1985). Results shown here indicate that recovery could take more than 20 years.

Mangrove communities occur between high and low tides and elevation of shoreline due to sea-level rise would leave mangroves in deeper waters and exposed to erosion from wave action. In addition, sea-level rise will increase water volume and this could alter the salinity regime of bays and estuaries in Texas (Montagna *et al.* 2007). Ning *et al.* (2003) have reported that a 20-inch sea level rise would cause large losses of mangroves in southwest Florida (where most of the mangroves of the United States occur).

Although climate change is expected to cause an increase of 3 - 7 °C (5.4 – 12.6°F) in the Gulf of Mexico region (Twilley *et al.* 2001), it is important to note that mangrove populations are affected by anthropogenic disturbances as well. Most changes in Harbor Island could have been caused by modification by dredging and

channel construction. Intense dredging activities occurred between 1958 and 1975 (Pulich *et al.* 1997). Particularly, the southwest corner of the island has been subject to dredging and channelization due to oil and gas exploration and from disposal of dredge material excavated from the Corpus Christi Ship Channel. It has also been reported that nearshore areas that were covered by vegetation in 1975 have been buried by discharge of dredge material in 1994.

Because of their location in the front line between the ocean and land, mangroves in the Gulf of Mexico also face natural threats such as hurricanes. The area of mangrove forest impacted in Texas by hurricanes has not been quantified. However, in Mexico between 10,000 and 14,000 ha have been lost annually due to hurricane impact since 1980 (FAO 2007).



Figure 4.9. Red mangrove (*Rhizophora mangle*) seeds in “Big Shell Beach” in Padre Island National Seashore, Texas after hurricane Dolly in July 2008. Photo by Jace W. Tunnell (08/02/08).

## Red Mangroves

Red mangroves have been observed in the southern coast of Texas since 1983 (Tunnell 2002). Recent hurricane activity appears to be facilitating the invasion of Red mangroves (*Rhizophora mangle*) to the Texas coast because of the observation of seeds on Gulf beaches (Figure 4.9). Red mangrove individuals are established in bays between South Padre Island and Matagorda Island and have increased since the 2005 intense hurricane season (Montagna *et al.* 2007). The proximity of Harbor Island to Aransas Pass, the Gulf inlet, explains the recent appearance of red mangrove there (Figure 4.10). Recently, Zomlefer *et al.* (2006) documented the most northern occurrence of red mangrove to latitude 29° 42.94' N in St. Johns County in Florida on the Atlantic Ocean side. These findings suggest that all mangrove species are expanding their range northward.



Figure 4.10. Red mangrove in Harbor Island, Texas (July 2006).

## CONCLUSIONS

The Texas coast may be one of the best places on Earth to observe climate change effects outside of the Polar Regions, because the major physical drivers, such as temperature, rainfall, and sea-level rise all can have large and interacting effects in the northwestern Gulf of Mexico region, and indicator species for climate change effects exist to illustrate the story. There are two direct effects, which are already observable, in the instrumental record: rapid sea-level rise and rising sea temperatures. The sea-level rise rates are high because of subsidence, which causes the relative rise to be that much greater. The increasing temperatures are already manifesting indirect changes in habitats and water quality.

Black mangroves, which are sensitive to freezes, are expanding northward. Even more cold sensitive species such as the red mangrove are showing up on the Texas coast. However, rapid sea-level rise may interact with habitat change to alter the trajectory of succession of coastal landscapes. It is not clear exactly what will happen.

One possibility is that sea-level rise simply drowns wetland habitats. But as long as plant growth and soil stabilization by plant roots occurs at a rate higher than apparent sea-level rise, then the habitats can simply move with moving shorelines. However, there is little reason to conclude that shorelines will not change.

Water quality change may be the most pernicious change of all even though this is an indirect change driven by the lower solubility of oxygen in warmer water. The potential for hypoxia, which are low dissolved oxygen conditions, is very great and increasing. Coined “dead zones” by the media, hypoxic areas are known to be large and expanding in number, extent, and duration. Hypoxia is known to be very destructive to coastal ecosystems, and leads to lower biomass, productivity, diversity, and can alter food webs such that desirable species can no longer be produced in an area. Whereas hypoxia is known to be caused by excess loading of nutrients from watersheds to coastal waters, it is clear that physical processes also play a role in lowering dissolved oxygen concentrations.

While earlier studies focused on how rainfall and consequent freshwater inflow changes might alter systems, there is no evidence in the recent instrumental record that salinities are changing along the Texas coast. Focus should be placed on adaptation to hydrological changes in climate. This would include better coastal planning so that human activities account for changing coastlines and habitats, and more concern about nutrient reductions. If climate change drives down dissolved oxygen concentrations, then the only recourse to adapt to this condition will be to put further controls on nutrient additions to coastal waters.

## **ACKNOWLEDGEMENTS**

Authors thank Nicole Selly, who digitized the mangrove distribution maps and Judith Clarkson, who wrote the introductory sections on “Texas Estuaries” and “River Basins”.

## **REFERENCES**

- Applebaum, S., P.A. Montagna, and C. Ritter. 2005. Status and trends of dissolved oxygen in Corpus Christi Bay, Texas, U.S.A. *Environmental Monitoring and Assessment* 107: 297-311.
- Anderson, J.B., 2007, Formation and Future of the Upper Texas Coast, Texas A&M Press, 163 pp.
- Britton, J.C., and B. Morton. 1989. Shore Ecology of the Gulf of Mexico. University of Texas Press, Austin, 387 pp.
- Bruun, P. 1962. Sea-level rise as a cause of shore erosion. *Journal of the Waterways and Harbors Division* 88: 117-130.
- Davis, R.A. Jr., Fingleton, W.G., Allen Jr., G.R., Creales, C.D., Johanns, W.M., O'Sullivan, J.A., Reive, C.L., Scheetz, S.J., and Stranaly, G.L. 1973. Corpus Christi Pass: A hurricane modified tidal inlet on Mustang Island, Texas. *Contributions in Marine Science* 17: 123-131.
- Diaz, R.J. and R. Rosenberg. 2008. Spreading dead zones and consequences for marine ecosystems. *Science* 321: 926 – 929.
- Douglas, B.C. 1991. Global sea level rise. *Journal of Geophysical Research*. 96: 6981-6992.
- Emanuel, K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years: *Nature* 436: 686-688.

- Everitt, J.H. and F.W. Judd. 1989. Using remote-sensing techniques to distinguish and monitor black mangrove (*Avicennia germinans*). *Journal of Coastal Research* 5: 737-745.
- FAO. 2007. The World's Mangroves 1980-2005. Food and Agriculture Organization of the United Nations (FAO), Forestry Paper 153, Rome, 77 pp.
- Field, C.D. 1995. Impact of expected climate change on mangroves. *Hydrobiologia* 295: 75-81.
- Gibeaut, J.C. and Tremblay, T.A. 2003. Coastal Hazards Atlas of Texas: A Tool for Hurricane Preparedness and Coastal Management - Volume 3: Austin, Texas, Bureau of Economic Geology, The University of Texas at Austin, p. 29.
- Gibeaut, J.C., White, W.A., Smyth, R.C., Andrews, J.R., Tremblay, T.A., Gutiérrez, R., Hepner, T.L., and Neuenschwander, A. 2003. Topographic variation of barrier island subenvironments and associated habitats, Coastal Sediments '03: Crossing disciplinary boundaries: Proceedings, Fifth International Symposium on Coastal Engineering and Science of Coastal Sediment Processes, Volume CD-ROM: Clearwater Beach, Florida, p. 10.
- IPCC. 2007. Climate Change 2007: The Physical Science Basis, Summary For Policy Makers. Intergovernmental Panel on Climate Change, Paris, 21 pp.
- Judd, F.W. 2002. Tamaulipan biotic province. In: Tunnell, J.W., Jr. and F.W. Judd (eds.), *The Laguna Madre of Texas and Tamaulipas*, Texas A&M University Press, College Station, 38-58.
- Kathiresan, K., and B.L. Bingham. 2001. Biology of mangroves and mangrove ecosystems. *Advances in Marine Biology* 40: 81-251.
- Larkin, T. J. and G. W. Bomar. 1983. Climatic Atlas of Texas. Texas Department of Water Resources. Austin, Texas. 151 pp.
- Longley, W. L., 1994. Freshwater Inflows to Texas Bays and Estuaries: Ecological Relationships and Methods for Determination of Needs. Joint Estuarine Research Study: Texas Water Development Board and Texas Parks and Wildlife Department.
- Longley, W. L. 1995. Estuaries. In: North, G. R., J. Schmandt, and J. Clarkson (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.
- Lot-Helgueras, A., C. Vazquez-Yanez, and F. Menendez. 1975. Physiognomic and floristic changes near the northern limit of mangroves in the Gulf coast of Mexico. In: Walsh, E., S.C. Snedaker and H.J. Teas (eds.), *Proceedings of the International Symposium on Biology and Management of Mangroves*, Vol. I, G. University of Florida, Gainesville, pp. 52-61.
- McMillan, C. 1975. Adaptive differentiation to chilling in mangrove populations. In: Walsh, G., S. Snedaker, and H. Teas (eds.), *Proceedings of the International Symposium on the Biology and Management of Mangroves*, Vol. I, University of Florida, Gainesville, pp. 62-68.
- Miller, L. and Douglas, B.C. 2004. Mass and volume contributions to twentieth-century global sea level rise. *Nature* 428: 406-409.
- Montagna, P.A., J.C. Gibeaut, and J.W. Tunnell, Jr. 2007. South Texas climate 2100: coastal impacts. In: Norwine, J. and K. John (eds.), *The Changing Climate Of South Texas 1900-2100: Problems And Prospects, Impacts And Implications*, Texas A&M University-Kingsville, pp. 57-77.
- Morton, R., Bernier, J., and Barras, J. 2006. Evidence of regional subsidence and associated interior wetland loss induced by hydrocarbon production, Gulf Coast region, USA. *Environmental Geology* 50: 261-274.

- Morton, R.A., and Paine, J.G. 1984. Historical Shoreline Changes in Corpus Christi, Oso, and Nueces Bays, Texas Gulf Coast. Austin, Texas, Bureau of Economic Geology, The University of Texas at Austin, p. 66.
- Ning, Z.H., R.E. Turner, T. Doyle, and K. Abdollahi. 2003. Preparing For A Changing Climate: The Potential Consequences Of Climate Variability and Change - Gulf Coast Region. US Environmental Protection Agency, GCRCC and LSU. Baton Rouge, 80 pp.
- Orlando, S. P., Jr., L. P. Rozas, G.H. Ward, and C.J. Klein, 1993. Salinity Characteristics of Gulf of Mexico Estuaries. Silver Spring, MD: National Oceanic and Atmospheric Administration, Office of Ocean Resources Conservation and Assessment. 209 pp.
- Overpeck, J.T., Otto-Bliesner, B.L., Miller, G.H., Muhs, D.R., Alley, R.B., and Kiehl, J.T. 2006. Paleoclimatic evidence for future ice-sheet instability and rapid sea-level rise. *Science* 311: 1747-1750.
- Paine, J.G. 1993. Subsidence of the Texas coast: inferences from historical and late Pleistocene sea levels. *Tectonophysics* 222: 445-458.
- Paine, J.G. and Morton, R.A. 1993. Historical Shoreline Changes in Copano, Aransas, and Redfish Bays, Texas Gulf Coast: Austin, Bureau of Economic Geology, The University of Texas at Austin, p. 66.
- Prouty, J.S. and Prouty, D.B. 1989. Historical back barrier shoreline changes, Padre Island National Seashore, Texas. *Gulf Coast Association of Geological Societies* Volume XXXIX: Transactions 481-490.
- Pulich, W., Jr. 2007. Texas coastal bend. In: Handley, L., D. Altsman, and R. DeMay (eds.), *Seagrass Status And Trends In the Northern Gulf of Mexico: 1940-2002*, US Geological Survey Scientific Investigations Report 2006-5287 and US Environmental Protection Agency 855-R-04-003, Reston, 267 pp.
- Pulich, W., Jr., and R.S. Scalan. 1987. Organic carbon and nitrogen flow marine cyanobacteria to semiaquatic insect food webs. *Contributions in Marine Science* 30: 27-37.
- Pulich, W., Jr., C. Blair, and W.A. White. 1997. Current status and historical trends of seagrass in the Corpus Christi Bay National Estuary Program study area. Natural Resource Conservation Commission, Publication CCBNEP-20, Austin, 131 pp.
- Ratzlaff, K.W. 1980. Land-surface subsidence in the Texas coastal region. Austin, Texas, United States Department of Interior Geological Survey, p. 19.
- Rignot, E., and Kanagaratnam, P. 2006. Changes in the velocity structure of the Greenland Ice Sheet. *Science* 311: 986-990.
- SAS Institute, Inc. 2004. SAS/STAT® 9.1 User's Guide. Cary, NC: SAS Institute Inc.
- SAS Institute Inc. 2006. SAS® 9.1.3 Language Reference: Dictionary, Fifth Edition, Volumes 1-4. Cary, NC: SAS Institute Inc.
- Seager, R., M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H.-P. Huang, N. Harnik, A. Leetmaa, N.-C. Lau, C. Li, J. Velez, and N. Naik. 2007. Model projections of an imminent transition to a more arid climate in Southwestern North America. *Science* 316: 1181-1184.
- Sharp, J.M., Jr., Germiot, S.J., and Paine, J.G. 1991. Re-evaluation of the causes of subsidence along the Texas Gulf of Mexico coast and some extrapolation of future trends. Fourth International Symposium on Land Subsidence, Volume 200, IAHS, p. 397-405.
- Shepherd, A., and Wingham, D. 2007. Recent sea-level contributions of the Antarctic and Greenland Ice Sheets. *Science* 315: 1529-1532.

- Sherrod, C.L. 1980. Present and Past Distribution of Black mangrove (*Avicennia germinans* [L.] L.) on the Texas Gulf Coast. Thesis (M.A.), University of Texas at Austin, 66 pp.
- Sherrod, C.L., and C. McMillan. 1981. Black mangrove, *Avicennia germinans*, in Texas: past and present distribution. *Contributions in Marine Science* 24: 115-131.
- Sherrod, C.L., and C. McMillan. 1985. The distributional history and ecology of mangrove vegetation along the Northern Gulf of Mexico coastal region. *Contributions in Marine Science* 28: 129-140.
- Spalding, M., M. Kainuma, L. Collins. 2009. World Atlas Of Mangroves. Earthscan, UK, 304 pp.
- 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.
- Tomlinson, P.B. 1986. The Botany Of Mangroves. Cambridge Tropical Biology Series, Cambridge University Press, Cambridge, UK, 413 pp.
- Tremblay, T.A., J.S. Vincent, and T.R. Calnan. 2008. Status and Trends Of Inland Wetland and Aquatic Habitat In The Corpus Christi Area. Coastal Bend Bays and Estuaries Program, Publication Number 55, Corpus Christi, 89 pp.
- Tunnell, J.W., Jr., 2002. The Environment. In: Tunnell, J.W., Jr. and F.W. Judd (eds.), The Laguna Madre of Texas and Tamaulipas, Texas A&M University Press, College Station, pp. 73-84.
- Twilley, R.R., E.J. Barron, H.L. Gholz, M.A. Harwell, R.L. Miller, D.J. Reed, J.B. Rose, E.H. Siemann, R.G. Wetzel, and R.J. Zimmerman. 2001. Confronting Climate Change in the Gulf Coast Region. The Union of Concerned Scientists, Cambridge, Massachusetts, and Ecological Society of America, Washington, D.C.
- Webster, P.J., G. J. Holland, J. A. Curry, and H.-R. Chang. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* 309: 1844 -1846.
- Wentz, F.J., L. Ricciardulli, K. Hilburn, and C. Mears. 2007. How much more rain will global warming bring? *Science* 317: 233-235.
- White, W.A., Morton, R.A., Kerr, R.S., Kuenzi, W.D., and Brogden, W.B. 1978. Land and Water Resources, Historical Changes, and Dune Criticality: Mustang and North Padre Islands, Texas. Austin, Bureau of Economic Geology, The University of Texas at Austin, p. 46.
- White, W.A., Morton, R.A., and Holmes, C.W. 2002. A comparison of factors controlling sedimentation rates and wetland loss in fluvial-deltaic systems, Texas Gulf coast. *Geomorphology* 44: 47-66.
- White, W. A., T. A. Tremblay, R. L. Waldinger, T. R. Calnan. 2006. Status and trends of wetland and aquatic habitats on Texas barrier islands Coastal Bend. Coastal Coordination Division, Texas General Land Office. Final Report, No. NA04NOS4190058, 78 pp.
- Williams, H.F.L. 1999. Sand-spit erosion following interruption of longshore sediment transport: Shamrock Island, Texas. *Environmental Geology* 37: 153-161.
- Withers, K. 2002. Wind-tidal flats. In: Tunnell, J.W., Jr. and F.W. Judd (eds.), The Laguna Madre of Texas and Tamaulipas, Texas A&M University Press, College Station, pp. 114-126.
- Zervas, C. 2001. Sea Level Variations of the United States 1854-1999, NOAA, National Oceanographic and Atmospheric Administration, p. 66.

- Zimmerman, R. J., T. J. Minello, E. F. Klima, and J. M. Nance. 1991. Effects of accelerated sea-level rise on coastal secondary production. In: Bolton H. S. and O. T. Magoon (eds), Coastal Wetlands Zone '91 Conference-ASCE, Long Beach, California, pp. 110-124.
- Zomlefer, W.B., W.S. Judd, and D.E. Giannasi. 2006. Northernmost limit of *Rhizophora mangle* (red mangrove; Rhizophoraceae) in St. Johns County, Florida. *Castanea* 71: 239-244.

