ECOLOGY OF SANDY BEACH INTERTIDAL MACROINFAUNA ALONG THE UPPER TEXAS COAST

A Dissertation

by

ANGELA DAWN WITMER

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2011

Major Subject: Zoology

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Approved by:

Chair of Committee,	Mary K. Wicksten
Committee Members,	Gil Rosenthal
	Christopher Mathewson
	Russell Feagin
Head of Department,	U.J. McMahan

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ABSTRACT

Ecology of Sandy Beach Intertidal Macroinfauna Along the Upper Texas Coast.

(May 2011)

Angela Dawn Witmer, B.S.; M.S., New Mexico State University

Chair of Advisory Committee: Dr. Mary K. Wicksten

Open coastlines are dynamic environments which experience seasonal and long-term physical changes. Sandy beaches line much of this coastline. As part of the requirements for Ph.D., I conducted a study examining intertidal macrofaunal and sedimentological features along the upper Texas coastal from 2007-2009. Four sites near Sabine Pass, High Island, Jamaica Beach, and Surfside Beach were selected. Beach transects were established at each site with six intertidal stations identified for collecting macrofaunal sediment core samples.

Although sandy beaches are low in species diversity, the taxa found survive under dynamic and harsh conditions. In disturbance dominated environments, sandy beach fauna tended to be influenced by physical factors, instead of biologically controlled ones. The taxa found in this study include primary and secondary successional organisms which are adapted to handle disturbances. 98% of the benthic specimens identified belonged to six taxa with 92% from two taxa, *Scolelepis squamata* (38%) and Haustoriidae (54%). Macrofaunal zonation varied between sites because of beach geomorphology.

On September 13, 2008, Hurricane Ike made landfall on the upper Texas coast causing extensive damage and erosion. Roughly 0.5 m of vertical height was lost at each beach post-storm. Total macrofaunal abundance declined by 87% from pre-storm counts. During the recovery the dominant two taxa, Haustoriidae and *Scolelepis squamata*, made up 82.78% of the total benthic specimens identified with haustoriids making up 68% of the total benthic taxa. The beach community remained dominated by four of the previously identified, six most common and abundant taxa.

Recovery of sandy beaches often was hindered by increased vehicular traffic, sand removal and cleaning. Beach ecosystems have shown a high natural ecological resilience, but do not preclude the possibilities of habitat extinction and/or catastrophic community regime shift. Beaches are highly susceptible to human exploitation and global climate change, such as sea level rise. Knowledge of beach macrofaunal diversity along the Texas coast, such as haustoriids, could be used to estimate beach health and better evaluate the upward effects of natural disturbance, pollution and human uses on an integral part of the coastal ecosystem.

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I first want to thank Dr. Wicksten for accepting me into her lab, giving me a forum to try out my ideas and thoughts on beach ecology. Thanks for seeing my potential. I also want to thank my committee members who were of great assistance in rewrites of drafts and this final product among other things. Dr. Christopher Mathewson was instrumental in teaching me the necessary survey skills and helping me with geological specimens. The use of his survey equipment incorporated an invaluable aspect to my research. Dr. Gil Rosenthal will ever be an invaluable guide to my professional career. Discussions on future career choices and postdoctoral assignments were greatly appreciated. Dr. Rusty Feagin gave me my first opportunity and paycheck as a coastal ecologist. My field research began on a positive note from that initial experience.

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CHAPTER I

INTRODUCTION

1.1 Beaches and sediment

Sandy beaches are found on every coast in the United States with Texas having over 600 miles of sandy beaches (Andrews, 1977). Sandy sediments are defined by the sediment grain size of 600-63µm (Wentworth Scale) (Wentworth, 1922). The term beach comes from the deposition of sediment through waves (Woodroffe, 2002). The source of sediments may come from many places including rivers, glacial deposits, continental erosion, and animals (King, 1972; Woodroffe, 2002). Although the sandy beaches in Texas are lithogenous (land) in origin, transported to the coast by rivers, they differ in grain size and mineral composition (Britton and Morton, 1989). There are 9 major Texas rivers which empty into the Gulf of Mexico or coastal bays. The rivers from north to south and the endpoints into the Gulf of Mexico include: Sabine River - Sabine Pass, Neches River -Sabine Lake, Trinity River -Trinity Bay/ Galveston Bay system, Brazos River -Brazos River Delta, Colorado River -Matagorda Bay, Guadalupe River -San Antonio river near San Antonio Bay, San Antonio River -San Antonio Bay, Neuces River -Corpus Christi Bay, Rio Grande River -Rio Grande River Delta.

Sand found along the northeastern portion of the Texas coast from Mississippi and Sabine River sediments is very fine and easily resuspended within the water column

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This dissertation follows the style of Estuaries, Coastal and Shelf Science.

(Britton and Morton, 1989). The central portion of the coast obtains its sand from the rivers in central Texas, mostly the Brazos and Colorado River systems, leading to the uniform, small grain size (Bullard, 1942; Minter, 1976; Britton and Morton, 1989). The southern/ lower portion of the state's beach sands is derived from the Rio Grande and lower Texas river drainage. The sand is small with a well sorted grain size which contributes to the less particulate disturbed waters (Bullard, 1942; Britton and Morton, 1989). Sedimentation available for deposition decreases from north to south. The Mississippi and Sabine Rivers, central Texas rivers, and lower Texas drainage produce an average sediment load into the Gulf of Mexico of respectively 230 million tons per year, 11.1 million tons per year, and 0.8 million tons per year (Meade and Parker, 1984). Longshore sediment transport along the upper coast has decreased in recent geologic history with a decrease in sediment outflow from the Mississippi River (Dunbar et al., 1992; Barras et al., 1994; Watson, 1999).

Beach sediment can be very harsh for animals in the swash zone. The constant movement of beach grains can abrade and kill animals. Grain size may vary from large gravel/ pebbles and shells to fine silt and clay. One beach alone may exhibit varying grain size depending on the time of year caused by the movement of sand offshore in the winter months. Grain size variation may change with seasonal beach profiles. During the summer months the grain size is much smaller as sand is deposited. In winter months the lighter, fine sand and silt is carried offshore into longshore bars and the heavier, coarser sand remains (King, 1972; Woodroffe, 2002). Beach face grain size may vary by eroding or accreting beaches. Where erosion is an issue, sand and silt may be removed leaving clay and bedrock behind. On sustaining, accreting beaches grain size may be similar winter to summer with only a slight difference in size as the finer particles are moved offshore (King, 1972). Texas coastal beaches range from eroding with rock and clay substrate to accreting fine sand and silt (Bullard, 1942; Britton and Morton, 1989).

1.1.1 Texas coastline

The coast of Texas is lined with a series of barrier islands except along two sections of coastline, Sabine Pass to Gilchrist and Freeport to Sergeant Beach. Texas barrier islands were created by the rise and fall of sea level with the present formation remaining after the last major sea level fall ~5,000 years ago (Britton and Morton, 1989; Anderson 2007). A major factor in creation of spit and elongation of barrier islands is longshore drift/current. In the northern part of the state, the longshore current moves sediment from the Mississippi and Sabine Rivers southward to North Padre Island. The Mexico/south Texas longshore current moves from the south, northward (Britton and Morton, 1989). These two opposing currents meet approximately at Big Shell Beach on North Padre Island. The exact conjunction may vary seasonally (Fig. 1.1) (Watson and Behrens, 1971). Barrier islands endure erosional pressures from the open sea, providing protection to the mainland behind. Many barrier islands' open shorelines have been eroding with the result of the island's bayshore growing closer to the mainland (Britton and Morton, 1989).

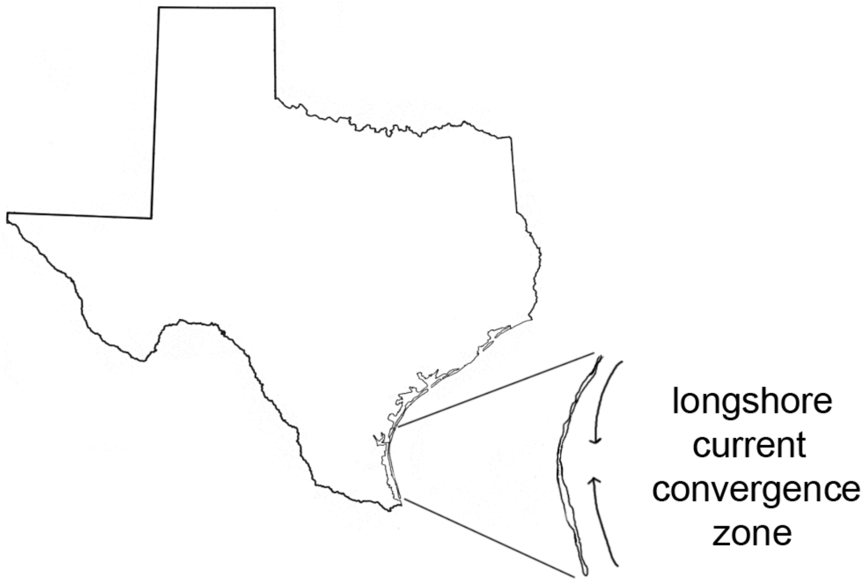

Fig. 1.1. Longshore current convergent zone along central Padre Island. Longshore currents from the north and south converge at Big Shell beach on Padre Island. Site varies around 27° N.

I divided the Texas coast into three regions based upon the longshore current and river influences: upper - Sabine to Brazos River; central - Brazos River to Big Shell beach; lower - Big Shell beach to Rio Grande River/ Mexico Border (Fig. 1.2). I examined the most threatened part of the Texas Coast, the upper region which is highly susceptible to erosion and changes caused by increased development and greater population (Anderson, 2007).

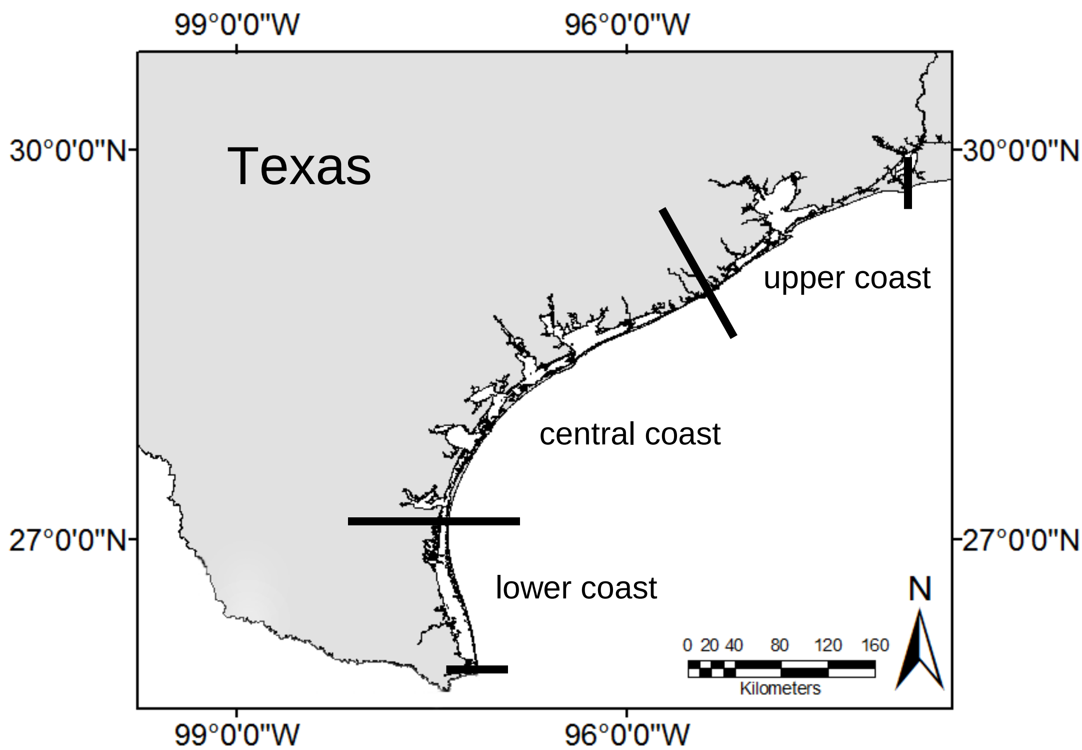

Fig. 1.2. Map of Texas coastline showing three divisions. Divisions are based upon Brazos River (separates upper and central) and the longshore current convergence at Big Shell beach, Padre Island (separates central and lower).

1.1.2 Physical environment

Various sediment types/environments influence the infaunal community structure found along the sandy shores. From the dune line through the swash zone animals utilize the environment for habitation and foraging. Sediment within the zone may change slightly as erosion of the beach face occurs more quickly on the foreshore (within the daily tidal regime) than the backshore, which may only be affected by the spring tides or storm driven waves. Beaches of larger sediment grain size denoted an eroding beach, with finer sediments more easily suspended. This large grain size can damage small organisms as the pebbles/ rocks grind against each other. The ability to hold water in the upper coarse sediment layer of these beaches is lower because of reduced capillary ability. These beaches tend to have fewer numbers of species and organisms (McLachlan, 1996). Finer sediment sizes and silt have less porosity but more surface area between the grains. Most benthic animals on average live within the top 10 cm, but this depth may vary by site (Keith and Hulings, 1965; Boudreau, 1998). Many larval organisms prefer a certain grain size when selecting a place to settle, although this restriction is not evenly consistent across populations within any sediment size range (Gray, 1974). Gray also noted that some species do not have a grain size preference, but settle according to available materials for home building or feeding.

Constructive and destructive waves vary seasonally and by storm events (Britton and Morton, 1989). During the fall and winter months the sand is pulled off the beaches and deposited offshore creating sandbars. During the summer sand from the sandbars is picked up through wave action and redeposited onto the beach creating a wider, gentler, sloping beach (Fig. 1.3) (King, 1972; Britton and Morton, 1989).

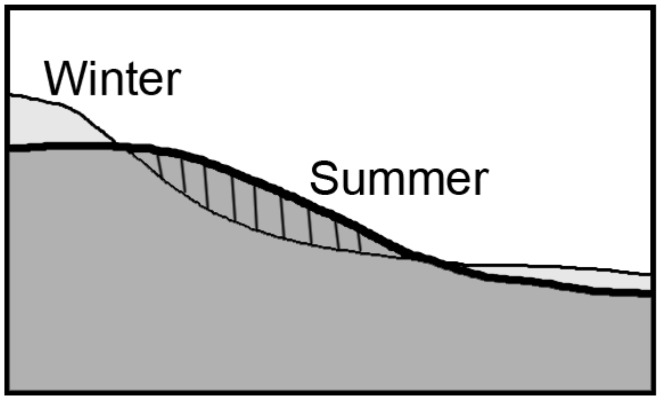

Fig. 1.3. Seasonal beach profiles. Thin line: a winter beach or a beach following a storm; Thick line: a summer beach.

Although the summer and winter seasonal changes create equilibrium with sediment transport on and off the beach face, there may be times during which the sand is not returned to the beach face. Instead storms can remove the sand from the “sand bank” nearshore allowing it to “leak” to a depth unattainable for transport back to the beach (Watson, 1999). Erosion along the beach face may also cause disturbance within the animal population. The recovery may take days to even years (Jaramillo et al., 1987). If erosion continues to the clay layer, the lightweight particles suspended within the water column are retained longer, thus transported a farther distance offshore. Sediment transport may also be interrupted by storm events moving sediment beyond the beach face into the back dunes creating sand aprons (Guidroz et al., 2007). Sediment may return to the beach face when water recedes, but much remains within the water inundated prairie and marsh lands.

Not only does natural disturbance occur along the beaches but Texas beaches are greatly impacted by human influence and changes (Anderson, 2007). Development along the coastline not only affects the coastal plants and animals, but also terrestrial species as they are displaced. Reports of coyotes in Galveston, Texas proper were attributed to the development on the western portion of the island (Schladen, 2008). Texas beaches are public property with only portions having restricted access according to the Open Beaches Act, 1959. Driving is permissible on Texas beaches. This not only hurts wildlife, causing disturbance, pollution, and noise; but it also compacts the beach making it unsuitable for burrows and more susceptible to erosion (Anders and Leatherman 1987). Property owners face erosion issues with their homes falling into the Gulf, i.e. at Surfside, Texas (Fig. 1.4). In 1929 the Army Corp. of Engineers moved the Brazos River to exit south of Surfside 10.5 km (6.5 mi.). The sediment accumulation from the delta also moved (Watson, 2007), causing erosion. Erosion issues at Surfside are also caused by sea level rise and the creation and lengthening of jetties.

Another example of human caused erosion along the upper Texas coast is Rollover Fish Pass, 3.2 km (2 mi) west of the High Island survey site. Watson (1999) described this manmade inlet, Rollover Fish Pass, connecting the Gulf of Mexico to East Bay, part of the Galveston Bay Complex. It was created in 1955 as a “fish pass” with original dimensions of 24 m (80’) across and 2.4 m (8’) deep. In the first year, the pass eroded to a width of 152 m (500’) and 9 m (30’) depth. Army Corps of Engineers in 1958 placed a steel bulkhead in an effort to curb the erosion of the channel banks. Although the channel erosion was curbed, erosion of the beaches along the peninsula increased greatly with current loss of sand at 200,670 - 242,477 m^3/yr (240,000 - 290,000 yd^3/yr).

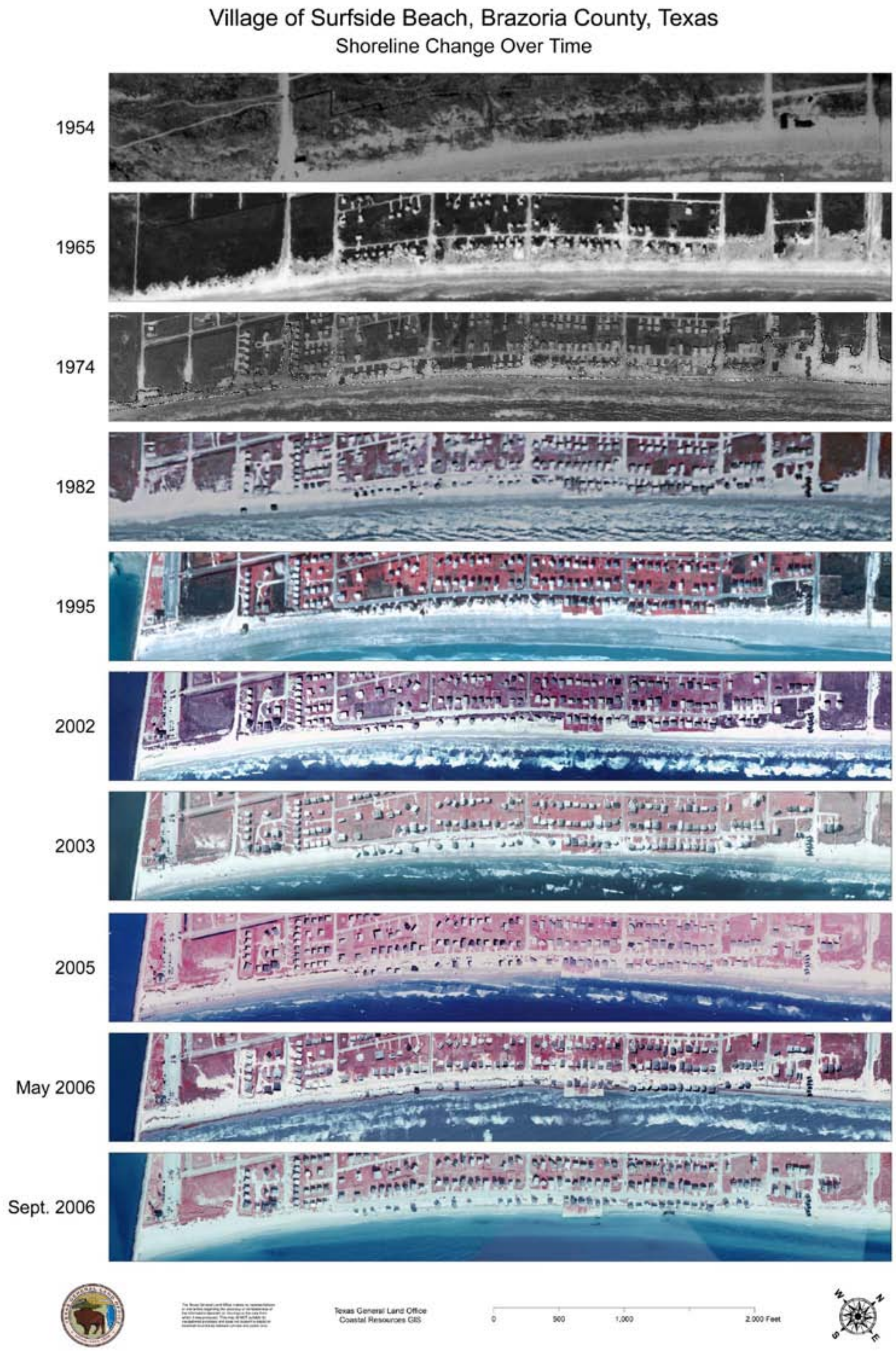

Fig. 1.4. Photos of Surfside, Texas from 1954 to 2006. Note the first line of houses in each successive photo becoming closer to the water line. Courtesy of Texas General Land Office.

Physical parameters of beaches vary from summer to winter in salinity, temperature, slope, and grain size consistency. Temperature changes follow the seasons; warmer in the summer, cooler in the winter. The cooling of air temperature directly influences the change in water temperature. The water temperature cooling occurs more slowly than land because water has a higher specific heat capacity (Giauque and Stout, 1936). Higher run-off from rains in the winter and spring will lower coastal salinity in contrast to summer months when lower amounts of freshwater and distance to river source retains the near open ocean values of salinity more consistently (Gray, 1981; McLachlan and Brown, 2006). High rainfall alone lowers salinity from 35 ppt to >10 ppt within minutes (Gray, 1981). Rivers have many effects on the coastal environment, such as debris deposition, sediment and nutrient transport, and salinity dilution. A surge of rain within the state causes rivers to swell and large influxes of freshwater and debris to be transported quickly into the Gulf. Nearly every year the Gulf of Mexico experiences a “dead zone” just off the Mississippi River Delta caused by excessive rainfall within the central portion of the United States which in turns brings excessive amounts of nitrogen fertilizers with the runoff (Graczyk, 2007).

The Gulf of Mexico is mostly a microtidal environment. Microtidal beaches are those with tides that are less than two meters vertical with exception of extreme spring tides and storm events (McLachlan and Brown, 2006). It is thought that the Gulf is microtidal because of the presence of a wide continental shelf, a shallow basin, low tidal effects, and being positioned outside of the major oceanic gyres (Martinez-López and Parés-Sierra, 1998). Microtidal, dissipative beaches provide a good opportunity to study biological zonation within the intertidal community, and the effects of season. The upper Texas coast has beaches described as dissipative, gentle sloping beach face, to intermediate (between reflective, steep beach face, and dissipative) (Wright and Short, 1984; Woodroffe, 2002; McLachlan and Brown, 2006).

1.1.3 Texas climatic events

There have been 57 hurricanes/major storms (~1527 to present) along the Texas coast, 17 major events (≥ category 3 or more than 100 people dead) (NHC-NOAA, 2010; Roth, 2010) (see appendix A). The events with the greatest effects were 1886 Indianola Hurricane (town leveled), 1900 Galveston Hurricane (6,000-8,000 dead), 1961 Hurricane Carla (54 dead; 2 billion in damage), 1980 Hurricane Allen (7 dead; $1 billion), 2005 Hurricane Rita (120 dead; $11.3 billion in damage), and 2008 Hurricane Ike (112 dead; $30.2 billion) (Knabb et al., 2006; Berg 2010; NHC-NOAA, 2010; Roth, 2010). Texas hurricane events have been increasing over the years (Britton and Morton, 1989; Goldenberg et al., 2001; Kerr 2006). The Gulf Coast experienced two major hurricanes in 2005; Hurricane Katrina had devastating effects felt from the Mississippi Delta eastward and Hurricane Rita made landfall over Sabine Pass, Texas. Hurricane Rita's greatest intensity offshore was a category 5 hurricane. It made landfall on September 24, 2005 as a category 3 (Knabb et al., 2006). The U.S. death toll from Hurricane Rita tallied 120. With Louisiana experiencing the brunt of the hurricane, damaging winds and rains tore apart roofs and homes in Sabine Pass, Port Arthur, Orange, and Beaumont, Texas. In 2007 Hurricane Humberto came ashore east of High Island, Texas as a category 1 hurricane. Although low in strength, this tightly packed hurricane grew from a tropical depression into a hurricane and hit land quicker than any other on record, 16 hours (Lozano and Sedensky, 2007). In 2008, Hurricane Ike made landfall in Galveston, Texas as a category 2 hurricane with a category 4 storm surge. This storm was very powerful bringing high winds and storm surge to the upper Texas coast. The results of these hurricanes will be examined in this study along with any other events that occurred during the two year study period. The question of global climate change being the cause of the increased number of category 4 and 5 hurricanes within recent history or whether we are experiencing a high cycle of increased hurricanes is under great debate (Goldenberg et al., 2001, Kerr, 2006). Whether in response to a multidecadal cycle or an increase of sea surface temperatures, expectations include an increase in the number of hurricanes and their strength (Goldenberg et al., 2001).

Other climatic or seasonal events along the Texas coast include cold fronts from the Arctic that deliver a quick frigid blast to the coast. The results of these events include high wind, higher seas, and cold temperatures. Effects on the beaches include greater erosion potential on winter beaches and migration of intertidal species to offshore, warmer waters (less affected by sudden temperature changes and rough seas) (Britton and Morton, 1989; Watson, 1999). Both of these summer and winter events occur annually along the coastal shores of the Gulf of Mexico, but the strength and duration of the events vary greatly with many recent Texas seasons ending quietly.

1.1.4 Beach research

Research on sandy beaches has been ongoing since the turn of the last century with interest in the effects of global climate change, sea level rise, human impact and erosion peaking within the past decade. Many prominent beach ecological principles such as ryhthmicity, plasticity, and mobility, have only been laid out this century (Schlacher et al., 2007).

Initial beach research examined physical descriptions of beaches, species richness and natural history, zonation, and ecology (Cornish, 1898; Stephen, 1928; Dahl, 1952; Bascom, 1964; Salvat, 1964; King, 1972; Gray 1974; McLachlan and Jaramillo, 1995). Dahl (1952) and Salvat (1964) were most noted for their work defining faunal zones on sandy beaches, creating a guide using varied factors for delineation. Dahl (1952) suggested three biological zones using dominant crustaceans for delineation. Although biological zones are easy to use, they must be retooled for each beach as some species may not occur on all coasts. Salvat (1964) created a four zone scheme based upon physical factors which may be more universally applicable. The two schemes are fairly comparable and overlap in the lower zones. Many researchers have opted to create a scheme of their own that works best in their region, following the pattern of Dahl's three biologically influenced zones or Salvat's four physical zones (Pollock and Hummon 1971; McLachlan, 1980, McLachlan and Brown 2006).

Disturbance and the effects upon the fauna was a topic of interest extensively studied in the 1970's with much interest examining the effects of storms on offshore benthic fauna, coral reefs, and intertidal communities (Table 1.1) (Boesch et al., 1976;

Yeo and Risk, 1979; Jaramillo et al., 1987; Posey et al., 1996; Dreyer et al., 2005). Most storms are considered pulse events having little statistical effect upon the fauna (Barnett, 1981; Posey et al., 1996; Dreyer et al., 2005). If the storm produced either of two physical results, freshwater influx and/or sediment change, fauna was effected (Keith and Hulings, 1965; Croker, 1968; Boesch et al., 1976; Yeo and Risk, 1979; Jaramillo et al., 1987). Most sediment change was the loss of the smallest grain size. The clay/silt fraction of the sediment was lost as seen after the 1979 Storm David in New England (Dobbs and Vorzarik, 1983). Schoeman et al. (2000) conducted an experiment removing 200 m^3 of beach sand simulating human clamming behavior on a beach. They found that these pulse events did not have adverse effects upon the macroinfauna. Instead they proposed that the removal of sand may have triggered a redistribution response in the neighboring individuals. Keith and Hulings (1965) surveyed the upper Texas coast sublittoral zone from September 1962 to September 1963. During the fall of 1963 Hurricane Cindy came ashore in Texas disturbing the infauna by dropping the salinity from normal sea levels to 18. Few to no organisms were recovered immediately post disturbance possibility related to turbulence, suffocation, and/or inability to withstand euryhaline conditions. Those that were identified post-hurricane included several polychaetes, *Donax* (clam), *Anomalocera* (copepod), *Mysis* (mysid) (possible misidentified genus), *Haustorius sp.* (amphipod), and *Neopanope* (crab).

Table 1.1. List of selected disturbance references. Includes examples of various types of disturbances occurring along coastlines from 1965 to 2005. See Sousa (2001) for extensive list.

Source (s)	Year	Disturbance type	Location	Animal studied	Study conducted
Keith and Hulings	1965	Hurricane	Upper Texas	Polychaetes, Crustaceans, Molluscs	1962-1963
Croker	1968	Hurricane (2)	Georgia	Amphipods	1964
Boesch et al.	1976	Tropical Storm	Lower Chesapeake Bay	Polychaetes, Amphipods, Molluscs	1972
Yeo and Risk	1979	Hurricane, storm	Minas Basin, Bay of Fundy	*Corophium*, *Macoma*	1975-1976
Barnett	1981	Severe storm	Humber Estuary, UK	Polychaetes, Oligochaetes, Nematodes, Copepods, Amphipods, Molluscs	1977-1978
Dobbs and Vozarik	1983	Storm David	Connecticut	Polychaetes, Crustaceans, Molluscs	1979
Anders and Leatherman	1987	Vehicles	New York	n/a	n/a
Jaramillo et al.	1987	Natural	New Hampshire	Polychaetes, Amphipods, Molluscs	1971-1983
Posey et al.	1996	Strong storm, 95mph winds	Florida, Gulf of Mexico	Polychaetes, Oligochaetes, Bivalves, Cephalochordates	1990-1991
Schoeman et al.	2000	Experiment	South Africa	Polychaetes, Amphipods, Crustaceans, Molluscs	n/a
Dreyer et al.	2005	Hurricane	O’ahu	Polychaetes, other major taxa	1992

The increase in Atlantic hurricane activity within the past decade (Goldenberg, 2001; Kerr, 2006) has brought the question to prominence, “what effect does climate change have on the coastal environment and the future of many species?” Previous work has been conducted in the upper Texas coast noting species richness and abundance (Keith and Hulings, 1965; Shelton and Robertson, 1981), but lack of seasonal data provides an incomplete picture of the biological world. Similar beach studies conducted elsewhere collected data seasonally selecting only one or two seasons (typically summer and/or winter) for sampling (Schoeman et al., 2003; Moreno et al., 2006; Rodil et al., 2006). Such studies may lack important information related to how species vary within and between seasons. With the exception of Lecari and Defeo (2003) who collected data on a sandy beach both bimonthly and multi-year, the literature lacks this type of intensive data collection. There are many examples of snapshot richness and abundance research without subsequent year data to support trends (Schoeman et al., 2003; Moreno et al., 2006; Rodil et al., 2006). Gray (1981) stated that studies less than one year were not adequate to demonstrate knowledge of annual, long term patterns and the species important to variation. Recent storm effects from hurricanes have made the upper Texas coast an ideal location to study baseline or community colonization/recolonization and identify and evaluate intertidal macroinfaunal recovery. Several authors stated that without a species baseline one cannot extrapolate how a system may change in response to an environmental event (Gray, 1974; Jaramillo et al., 1987; Dreyer et al., 2005).

1.2 Purpose/Hypotheses

Schlacher and others (2007) described several needs to better understand beach ecosystems and functions of which included “ecological consequences”, “functional relationships” between physical and biological environment, and “implication of habitat loss”. The intent of my research was to define the upper Texas coastal environment, ecological structure, communities, beach types, and evaluate seasonal changes and possible climatic events over a two year period. I investigated quantifiable patterns in beach faunal structure that are controlled by physical processes such as: seasonality, storm effects, shoreline loss/gain, river surge, traffic, climate change.

The purpose of this study was two-fold. Initially, I obtained baseline information on the seasonal composition of invertebrate macrofauna (animals larger than 1mm) along the upper Texas coast, along with various seasonal physical measurements, grain size of beach sand and beach profile. Secondarily, I quantified the changes to the invertebrate fauna in relation to major storm events, including river surge, tropical depressions, hurricanes, and arctic cold fronts. I proposed several hypotheses that were examined during this study. Those hypotheses were:

H1: There are no changes in beach elevation by season.

H1a: There are changes in beach elevation by season.

H2: There is no difference in sediment grain size by season.

H2a: There are differences in sediment grain size by season.

H3: There is no difference in sediment grain size between beaches.

H3a: There are differences in sediment grain size between beaches.

H4: There is no difference in sediment grain size between beaches North to South.

H4a: There are differences in sediment grain size between beaches North to South.

H5: There are no changes in invertebrate richness or abundance related by changing season.

H5a: There are differences in invertebrate richness or abundance related by changing season.

H6: There are no differences in taxa composition between beaches.

H6a: There are differences in taxa composition between beaches.

H7: There is no difference in taxa composition between eroding and sustaining beaches.

H7a: There are differences in taxa composition between eroding and sustaining beaches.

H8: There is no difference in abundance or richness after major storm (pulse) events.

H8a: There are differences in abundance and/or richness after major storm (pulse) events.

1.2.1 Expected results

Beaches along the upper coast although within 193 km (120 mi) of each other vary. I expected to find variations within each beach study area from low intertidal to high intertidal and between the beaches themselves from very fine sand (Surfside) to rocky, shell hash (High Island). I also expected to find taxa richness to decrease during the winter. Erosion and high traffic areas should have low macrofaunal taxa richness and abundance compared to those with less traffic and erosion issues. The presence of specific biota was an indicator of disturbance or a highly stressed environment. As storm events occurred I expected to find a greater number of disturbance/stress biota indicators such as the polychaetes *Lumbrineris, Haploscoloplos,* and *Scolelepis* (Keith and Hulings, 1965; Shelton and Robertson, 1981; Allen and Moore, 1987; Sweet, 1987).

My research used a multidisciplinary approach in viewing the ecosystem as a whole, utilizing the fields of invertebrate zoology, biology, oceanography, and geology. This is not a new way of thinking, as many naturalists of the previous centuries were required to be competent in multiple areas of science. Such an approach may help in the better understanding of the current state of our ecosystem along the upper Texas coast. This study did not consider the current coastline to be a pristine environment, but one undergoing changes through erosion and human impact/use. The results of this study may assist in better ecosystem management of coastal habitats and allow beaches to be graded upon recovery type based upon species composition. Incoming waves upon the beach provide infaunal animals planktonic organisms and algae to eat. Animals higher on the food chain such as large crabs, fish, and migratory birds frequent the swash zone foraging on infaunal organisms (i.e. polychaetes, amphipod, and molluscs) within the moving sands (Leber, 1982; Peterson et al., 2006).

CHAPTER II

ARMORING OF THE COASTLINE AND OTHER HUMAN MANIPULATIONS

2.1 Introduction

In an effort to reduce coastal retreat and erosion, humans have armored the coastline. The addition and creation of hard impenetrable structures at the land-sea interface was an effort to resist natural coast processes. Beaches are battered daily by waves, longshore current and tidal flow. This daily onslaught erodes a sediment deprived, subsiding coastline as the upper Texas coast. In an ideal world sediment loss/gain would have a net result of zero, but beaches are not a static environment. Within the past 100 years, rivers have been dammed reducing sediment flow to the coast, oil and water have been withdrawn from the ground causing the land to subside, and the coast line armored interrupting the longshore transport (Mathewson and Minter, 1981). Not only have we impacted our coastline, but natural variation and sea level rise are threatening our precious shores pushing them landward 0.5-3 m (2-10 ft) per year.

In this chapter I will review many of the structures placed upon the shoreline to prevent or reduce erosion and discuss various ways how human manipulation of the coastline has impacted the beach and its biota.

2.2 Hard structures

One of the largest structures used to reduce coastal retreat, erosion, and storm protection is the seawall. These large structures are made of reinforced concrete, rip rap and/or large boulders which moderate or negate the effect of waves and storms. There are several seawalls in United States from Key West to Seattle. The most prominent is the Galveston Seawall. Built in 1904-1905 as a response to the "Great Storm" (1900 Galveston hurricane) which claimed between 6,000-12,000 lives, this structure was to protect the city of Galveston from future hurricanes. The century old structure has been extended five times (last extension finished in 1961) to its current length of ten miles stretching along the northern gulf facing coastline (The Real Galveston.com, 2010). The Galveston seawall was built to a height of 5.2 m with a top width of 1.5 m and base width of 4.9 m lined by granite boulders. In 1900, elevation on Galveston Island was only 2.74 m with much of the island being much lower. Sediment was dredged from the channel and the Gulf to elevate the island and create a slope from the seawall downward to the bayside. The seawall has withstood several hurricanes and was only breached for the first time in 2008. Waves and surge from Hurricane Ike were forced over the seawall, assisting in flooding the lower parts of the city.

The seawall has many advantages which supported the proliferation of similar new structures around the world. In effect the seawall does its job, it stops erosion. These structures do require maintenance; continuous efforts must be made to prevent erosion from under the structure. Seawalls are also an effective barrier against storm surge and waves. If the structure has been created high enough, it also becomes the front line of defense for sea level rise. Advantages of the seawall are matched with several disadvantages. The seawall does not allow for natural retreat. At the point where the seawall ends, the downdrift end of the longshore current, a notch can be scoured into the coastline causing extensive erosion and instability (Fig. 2.1). The extreme erosion decreases as one continues down shore. Seawalls promote erosion. The loss of beach sand and width has been noted numerously in the literature (Pilkey and Wright, 1988; Kraus and McDougal, 1996; Fletcher et al., 1997; Morton, 1997; Griggs, 2005a). Any beach sand in front of the seawall can be effectively removed and sent down shore with the longshore current, continuing until it meets the structure. If the beach is not renourished, erosion will undermine the structure causing it to fail. Riprap along the base of the structure assists in the prevention of undermining. When the sea-level rises to the point that low tide does not expose the base of the structures, then the seawall effectively becomes a wave reflection cliff and the beach is lost. Overall nourishment has become more of a tourism/economic decision and not always a necessity for the stability of the structure.

Fig. 2.1. Southwest end of seawall in Galveston, Texas. Observe notch cut by longshore currents at end of seawall indicated by arrow. Photo taken in 2004 by Christopher Mathewson.

Other permanent structures found commonly along the coastline are jetties and groins. Jetties are structures of concrete, rip rap and/or granite boulders that line the shipping channels to reduce wave energy for safer ship movement. They also prevent migration of land into the shipping channel. The structures can extend several miles into the open sea interfering with the longshore current. Similarly made, groins are found along the open coastline extending out to sea for a few hundred meters. Their purpose is to reduce the amount of shoreline erosion by trapping sediment from the longshore current. Although it traps sand on the updrift side of the jetty or groin it also tends to erode sediment on the down drift side (Fig. 2.2). Longshore transport along the upper Texas coast runs from the northeast to the southwest.

Intertidal rocky habitat is new to the upper Texas coast. The naturally sandy/clay shores were hardened and reinforced toward the end of the 19th century to stabilize channels for shipping. The Galveston jetties lining Bolivar Roads were first established as gabions in 1874. Granite blocks were later used to line the established hard core jetties, first deposited in 1887 and continued as a preferred substrate for building harden structures (Sargent and Bottin, 1989). In the 1930's a series of 15 groins was established along the Galveston Seawall from 10th to 61st street, 6 km long field, 13 groins at 150 m, 2 at100 m (Ravens and Sitanggang, 2007). These structures were created in response to the 1900 hurricane and to retain as much beach along the seawall as possible.

Fig. 2.2. Groin off the Galveston, Texas seawall. Photo taken September 2008 after Hurricane Ike.

Groins break incoming wave producing an escape for water returning to the ocean. This return can create rip tides. It can also erode sediment from around the groins creating channels. After Hurricane Ike these channels were evident along the groins in Galveston, Texas (Fig. 2.3). In the photograph, the erosion on the northeast side of the groin channel (right) is not as prominent as the downdrift side (left). Jetties and groins are popular among fisherman taking advantage of the deeper channels nearshore and the fish that are attracted to them.

Fig. 2.3. Aerial photograph of the Galveston, Texas groin. Photo taken September 2008 after Hurricane Ike. Arrows indicate sediment eroded channels. Photo taken by Christopher Mathewson.

2.3 Soft/temporary structures

Geotextile tubes, aka geotubes or sand socks, are the most common soft/temporary structure to combat erosion. The lost cost of these structures has made them a favorable option for local governments interested in a semi permanent structure. In Texas regulations surrounding beach structures for coastal armoring are negated because the geotubes are considered "temporary". Geotubes are approximately 2.6 m in diameter with a 9 m circumference (Gibeaut et al., 2003; Heilman et al., 2008). The tube is made from a fibrous material which is then filled with a sandy substrate or concrete. These large structures could be found near Sabine Pass, Gilchrist, and Pirates Beach, Texas. They can be used to armor the coastline by being placed along the vegetative line, creating an artificial dune. In marshes it can reduce wave action on the sensitive land-water interface. These structures have also been placed perpendicular to the beach to trap sediment from the longshore current (Fig. 2.4). Hurricane Ike (2008) changed many locals thinking regarding geotubes. The extreme storm surge created havoc on the coastline at the point that geotubes were compromised. From photos it is evident that where geotubes remained intact, property behind the structure was protected (Fig. 2.5). The issue was in the adjacent lots where the geotubes failed. Many of the failures of geotubes occurred in the breaks for public access or storm drainage. Some geotubes were either destroyed or moved from its original position allowing for excessive damage to lots immediately behind the tube’s break. Much property damage was caused when water was funneled through the breaks which allowed for greater flow and force of water both onshore and offshore in the return flow (Mathewson, C., personal communication; Stiffler and Mathewson, 2009). Geotubes were successful in preventing some damage, but are also considered a potential hazard because of the failures that occurred during Hurricane Ike. In response many of the local governments have removed the geotube structures. Currently there are petitions from the low-lying coastal communities for a permanent structure such as seawall to be constructed (i.e. Gilchrist, Bolivar Peninsula).

Fig. 2.4. Geotubes perpendicular to shoreline at McFadden National Wildlife Refuge. Photo by Archie W. Ammons.

Fig. 2.5. Geotubes and enhanced erosion at breaks. Aerial photograph taken September 2008 near Gilchrist, Texas on Bolivar Peninsula. Photo by Christopher Mathewson.

Several other soft/temporary structures attempted to stop beach erosion but with some limited success, include haybale dunes, *Sargassum* dunes and Christmas tree dunes. The placement of plant debris along the upper beach/foredunes has been observed to trap sand and allow for new plant colonization. The limited success is in part because any major storm with significant waves can destroy these attempts of shoreline protection. If sufficient time has been given for these structures to become entrained into their environment they can have success in building dunes. Dunes provide stabilization and protection to the coastline buffering developed properties from small to moderate storms and waves (van der Meulen and Salman, 1996; Feagin et.al, 2005). Hay bales, *Sargassum* wrack, and Christmas trees have been placed along the foredunes in an effort to trap aeolian sand and create dunes (Fig. 2.6). These efforts are common along the coast as little funds are required.

Fig. 2.6. Haybales on the upper beach. Haybales were placed upon the upper beach face to trap sediment and create dunes on South Padre Island. Photo taken August 2005 by Archie W. Ammons.

Sargassum, gulf weed, is washed ashore each year beginning as early as March through September. This weed can attain a height of several feet high creating a natural barrier in the upper intertidal zone to the ocean. As the upper Texas coast is a popular tourist destination, smelly plants are not seen as a pleasant welcome to visitors. Local governments under the approval of the Texas General Land Office remove the weed and deposit it on the upper beach near the dunes or in some cases completely away from the local area. In many upper Texas coastal municipalities, the raking of *Sargassum* begins just before the Fourth of July and continues through Labor Day (Brick, J., personal communication). It is their intention to removal as little sand as possible retaining the integrity of the beach (Brick, J., personal communication). Placement of the raked sargassum has been noted to be an effective method of embryonic dune formation/retention (Davidson et al., 1991; Gheskiere et al., 2006) as observed in both Jamaica Beach and High Island (Fig. 2.7). With proper management it has been demonstrated that the removal of weed does not adversely affect the slope of the beach nor the meiofaunal invertebrates habituating the lower beach face (Gheskiere et al., 2006; Feagin and Williams 2008). The management of *Sargassum* has caused much debate for and against the removal the weed from the shoreline. Some local residents regard *Sargassum* as a natural erosion barrier, while others point out the economic/tourism benefits of large clean beach and removal of the smelly, unsightly view (Phillips and Jones, 2006; Williams et. al, 2008). A compromise of removal of weed from the lower beach face with subsequent deposition of *Sargassum* on the upper beach seems to favor both views rather than the additional expense of complete removal from the beach system (Fig. 2.7).

Fig. 2.7. Sargassum dunes at High Island, Texas. Note newly deposited sargassum impounding windblown sand (arrow). Photo taken December 2006.

The planting and placement of varying plant debris on coastlines has been conducted for decades in the effort to trap sand and stabilize dunes (Kroodsma, 1937; Avis, 1989; Carter, 1991). Haybale dunes placed along the foredunes work in much the same way (Fig. 2.6).

Christmas tree dune experiments have been a winter oddity along the upper Texas coast for numerous years with mixed results. Although they do trap windblown sand, dunes have been found to collapse as trees decay under the weight of the impounded sand. At the Surfside Beach site the use of Christmas trees as a means for creating dunes was recorded from December 2007 through August 2008 until Hurricane Ike ended the experiment (Fig. 2.8). Locals along with the county government placed/staked abandoned and donated Christmas trees on the beach near the foredunes in January 2008. Each month photographs of the placed discarded trees were taken to record the progress of impounding sand. From the sequence of photos it was observed that the placement of objects on the upper beach did trap sediment and created coppice mounds for the settlement of beach plants (Fig. 2.8). Some of these trees trapped larger items from storm wrack creating a larger surface area for trapping windblown sand. *Sporobolus* sp. (seashore dropseed) and *Seversium* sp. (sea purslane) were commonly observed settling and stabilizing these mounds at Surfside Beach. This undertaking, later called the DunesDay project, was reattempted in January 2009 after Hurricane Ike destroyed the upper beach face and low lying dunes. The fate and resultant effect of this second project was not followed in this study.

Fig. 2.8. Composite photo of 2008 Christmas tree dune attempt. Composite of sequential month's photos demonstrating evidence of trees trapping sand and debris.

2.4 Manipulation of the beach

With coastlines experiencing a rise in human population and greater tourism, the natural beach is becoming endangered. There are many ways people have manipulated the beach in an effort to clean or beautify them. Raking and grooming are common methods to remove and smooth out the beach face (Fig. 2.9). Debris from daily tides litters the beach with natural and artificial trash. Freshwater hyacinth (*Eichhornia* sp.), various marsh reeds, trash, and shells were commonly found in wrack lines.

Fig. 2.9. Raking on the beach. Large tractor rakes the beach at Crystal Beach, Texas removing debris and leveling the sand.

Each March through August, *Sargassum* is cast ashore littering the upper intertidal zone. Some years the gulf weed can pile up over a meter high as observed in July 2007. The weed was raked after accumulation. In Jamaica Beach the sargassum is raked just before July 4th continuing each week until September (Brick, J., personal communication). The results of the raking as discussed above are either removed completely from the beach system or placed on the upper beach. Not only are the beaches cleaned by raking, but the sand may be sifted to remove large particles. In February 2009 after Hurricane Ike, the city of Jamaica Beach sifted sand from the beach face and other piles of sand accumulation (Fig. 2.10). Sand was sifted to remove the dangerous debris such as wood, nails, metals, plastics, making it safer for the public. After sifting the sand, it was placed back on the beach. This act of removal and deposition was harmful to the recovery of the beach as it removed and buried organisms (Chapter VI).

Fig. 2.10. Sifting of sand outside of Jamaica Beach, Texas, February 2009.

Another type of invasive human activity is beach nourishment. This expensive measure replaces lost sand from natural retreat, erosion, or from storm removal. A nourishment project lasts 10-15 years depending upon amount of sediment deposited, barring large storms (Bird, 2008; Tresaugue, 2009). This short term measure does increase the sediment load available in the longshore transport as the deposited material mitigates downdrift (Griggs, 2005b). Materials used in nourishment projects are brought in from terrestrial or marine supplies. The timing of nourishment projects is important considering sea turtle's nest on the area beaches. Because of this, projects on the upper Texas coast are limited to winter months before or after "turtle season" (March – August). Another consideration of such projects along the upper Texas shores is the sediment grain size. Sediment for nourishment projects should be of the same grain size as previous beach sands. New sand is typically obtained from dredged material either from the local channels, ebb/flood tidal deltas, or offshore sources; all non-renewable resources after being cleaned by drying and sun bleaching (Bishop, et al., 2006; Speybroeck, et al., 2006; Watson, 2007). Many studies have been conducted examining renourishment and sediment sizes. It was found that the deposition of sediments could suffocate organisms if too fine a sediment was used (Menn et al., 2003; Bishop et al., 2006; Peterson et al., 2006; Speybrock et al., 2006). Finer sediment also caused increased turbidity which negatively affected animals both in the intertidal and subtidal zones.

Undesigned nourishment projects involved laying of materials without consideration of the lifetime, width and slope of beach post renourishment. These usually consisted of locally dredged materials (Morton, 1997). There have been several small renourishment projects of this type along the upper Texas coast (Ravens and Sitanggang, 2007). In contrast, designed projects involve specified plans with schedules, expectancy of the project and adequate sediment supply (Morton, 1997). Along the upper Texas coast there have been two such designed projects: 1995 and most recently 2009 (Fig. 2.11). The intent of the 1995 project was to last 15 or more years excluding any major storm variable (Tresaugue, 2009). Hurricane Ike modified that timeline by removing the beach in front of the seawall requiring an emergency decision to nourish the beach to save the seawall from undermining.

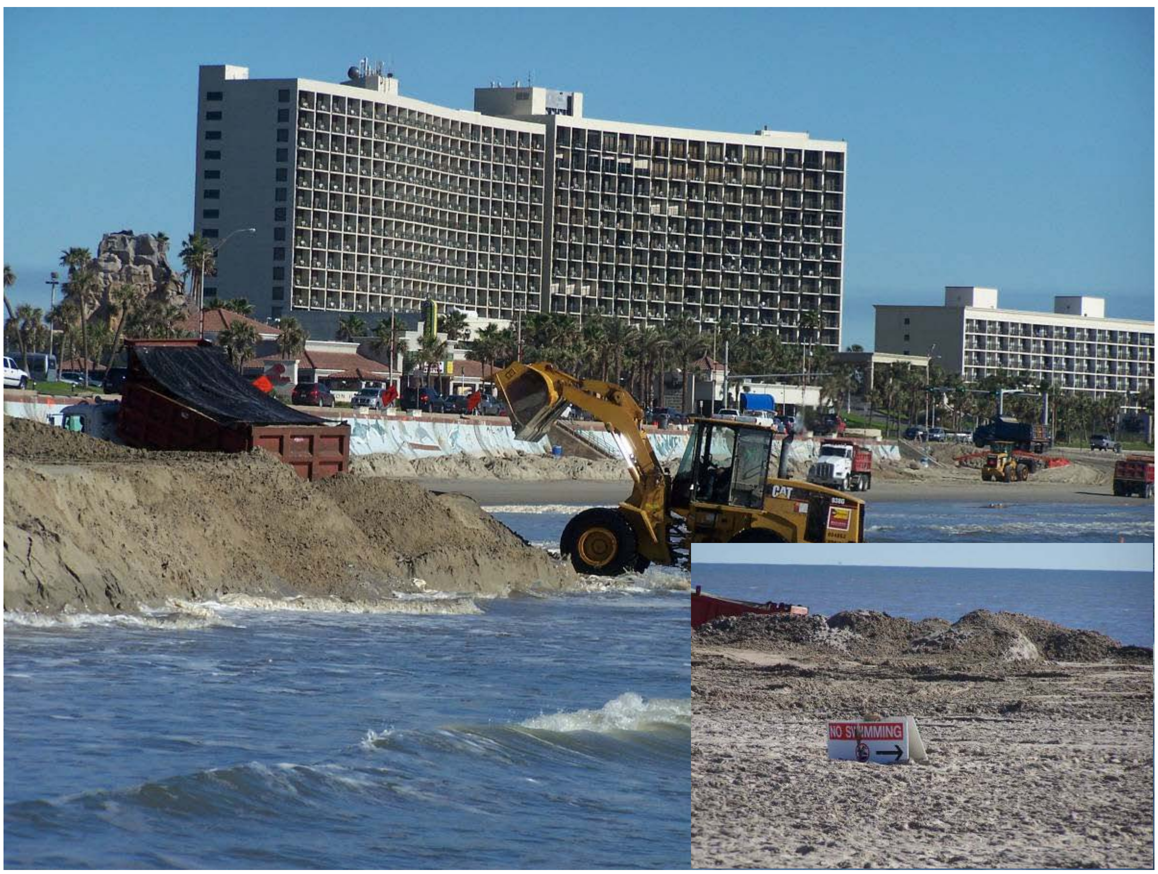

Fig. 2.11. Beach renourishment project, January 2009. Beaches were nourished from 10th to 63rd street in Galveston, Texas.

In December 2008 the Texas General Land Office and Galveston Island Park Board of Trustees began the process of replacing sand in front of the seawall. After Hurricane Ike, the beach was decimated and the seawall was in danger of being undermined. To prevent this and reenergize the tourism industry they deposited 457,200 m^2 of sand, 1.5 m high, 70 m out away from the seawall (Gaskins, 2008; McPherson, 2009; Stanton, 2009). The sand was deposited and reworked on the beach from 10th to 61st street (Gaskins, 2008). Large dump trucks emptied their load of sand on the beach as the bulldozers moved it into place, leveling it out. Cost for this project was $13.5 million (McPherson, 2009). Sand was locally dredged or excavated, sun-bleached, and trucked onto the beaches (Stanton, 2009).

2.5 Discussion

The influence of human activities “shoring” up the coastline is extensive. But does this slow down erosion/coastal retreat? What are the effects on the beach ecosystem? Both questions have been reviewed extensively in the literature. Although hard structures put a stop to erosion/retreat, they cannot permanently withstand nature. These structures must be maintained but maintenance cannot stop nature’s fury. The Galveston seawall has withstood a century of destructive hurricanes, but in 2009 Hurricane Ike damaged the seawall. The twelve hour onslaught of water and debris left sinkholes in the sidewalk on top of the seawall and exposed the century old wooden supports (Tresaugue, 2009). The immediate replacement of sand to rebury and protect the structure from undermining began three months after the hurricane, funded by emergency monies. The land directly behind such large structures seems to be protected, but the literature questions whether these structures slow down erosion. Hard structures have been noted to encourage erosion, narrowing the beach and increasing downdrift erosion on the flanking edge (Pilkey and Wright, 1988; Fletcher et al., 1997; Griggs, 2005a; Dugan et al., 2008). They also stop upland erosion, reducing the sediment supply to beach and downshore (Pilkey and Wright, 1988; Fletcher et al., 1997). Erosion affecting the beach and dunes also affects the organisms that live in such habitats. Hard structures eliminate open coastal dunes and development behind such structures eliminates dune habitats altogether.

Responses to the natural retreat and erosion of the coastal shoreline have caused much debate. There are two choices in the face of an eroding coastline: fight or retreat. Pilkey and Wright (1988) noted the choices as hard or soft stabilization, while Griggs (2005b) labeled these choices as remain, relocate/retreat, or armor the coastline. Fighting erosion actively can utilize two different methods: armoring the coastline with hard or soft structures as noted above or through beach renourishment. The second method is passively allowing the natural process of erosion to continue and to retreat along with the coastline. As each position has valid arguments, the best method to proceed with is best answered by the local stakeholders and management. The balancing of erosion, sea-level rise and conservation of endangered habitats is a constant battle as the economics of the region are often entwined with the response (Phillips and Jones, 2006; Schlacher et.al, 2007).

Stutz and Pilkey (2005) proposed a modeling system of human pressures on barrier islands. Their “geomorphic carrying capacity” measures a barrier island’s ability to respond both environmental and human influences. Although every barrier island is unique, a measurement might allow for better understanding of an island’s resilience before external pressures “terminate” it. Islands are “terminated” when the coastline no longer exhibits its inherent properties through the fortification of the land-sea interface (Stutz and Pilkey, 2005).

In conclusion, it is accepted that the coastline is undergoing natural retreat as subsidence and sea-level rise act upon it. It is also recognized that this may be accelerated by erosion whether naturally caused or man-made through reduced sedimentation (dams), structures stabilizing the coastline and channels, or the regional removal of underground natural resources. Human response to these problems may “terminate” the coastline and the species that are indigenous to the area. Mindful conservation and modification of behavior is the key to preserving the environment and its species for generations to come.

CHAPTER III

UPPER TEXAS COASTAL GEOLOGY

AND BEACH MORPHODYNAMICS

3.1 Introduction

Open coastlines are dynamic environments that experience seasonal and long term physical changes. There are many factors that may affect the coastline daily. Tides, waves and storms modify the coastline and create a dynamic land-water interface. Being climatically mild, the Texas coast is microtidal with tides less than 2 m. Low wave height with high energy also are typical along the shoreline as the gulf basin is dominated by wind waves (Britton and Morton, 1989). The coastline has undergone accretionary, sustaining and now erosional periods (McGowen et al., 1977). The shoreline of the upper Texas coast has been retreating since the end of the last ice age ~17,000 yrs ago. Sea level rise and subsidence have moved the shoreline drowning several river valleys to its current position, about 129 km (~80 mi) inland. Sea level rise and subsidence have changed the erosional coastline, drowning river valleys, ancestral barrier islands (i.e. Heald Bank, Sabine Bank) and the current shoreline.

The upper Texas coast has two major shoreline features, barrier island and spit peninsula. The Galveston barrier island began to develop 5,500 years ago, attaining the maximum size about 1,200 years ago (Anderson, 2007). Since that time the shoreline has been retreating. Follets Island is the southernmost, upper Texas coast barrier islands. The narrowing of this barrier island indicates that it is in the final stages of being completely eroded. Bolivar Peninsula is a spit created by the deposition of sand along the longshore current. Bolivar's formation began 2000 years ago (Anderson, 2007).

The composition of beach sediments along upper Texas coastal is mostly from lithogenous, sedimentary origins with underlying clay/muds (Bullard, 1942; Fisher et al., 1972; Fisher et al., 1973). Sands supplied from local rivers such as the Mississippi River, Atchafalaya River, Sabine River, Neches River and Trinity River have all experienced a reduction in sediment transport caused by man-made stabilization, change in hydrodynamic pressure and damming (McGowen et al., 1977; Morton, 1977; Dunbar et al., 1992; Barras et al., 1994; Morton 1997; Watson, 1999; Kesel 2003). This reduction of sedimentation along with the erosive effects of sea level rise, coastal armoring, and longshore current have exacerbated the shoreline retreat to the point of exposure of Pleistocene clay units along several severely eroding regions of the upper Texas coast (Fisher et al., 1972; Morton, 1997; Anderson 2007).

The beach is the sum of all the components. Interactions between the waves, tide, beach slope, and sediment grain size can assist in the understanding of macrofauna inhabiting this ecosystem. In this chapter I will attempt to define current geological and physical characteristics of the upper Texas coast.

3.2 Materials and methods

Four sites were selected for survey along the upper Texas Coast from the Louisiana Texas border to the old Brazos River delta. These sites were selected based on several criterions that are representative of the upper Texas coast and to increase probability of a storm landfall. Criterions include: distance from one another, location on barrier island vs. mainland, level of erosion, and human manipulation (Fig. 3.1; Table 3.1). Each site was named by the nearest municipality:

- Sabine Pass– Beach entrance 3 adjacent to the McFaddin National Wildlife Refuge, 19.3 km (12 mi) west of Sabine Pass, Jefferson County, Texas
- High Island - SH 87 and 124 intersection, 0.97 km (0.6 mi) south of High Island, Galveston County, Texas
- Jamaica Beach – Beach off Buccaneer St. in Jamaica Beach, Galveston County, Texas
- Surfside Beach – Beach access 5 off county road 257 , 8 km (5 mi) east of Surfside Beach, Brazoria County, Texas

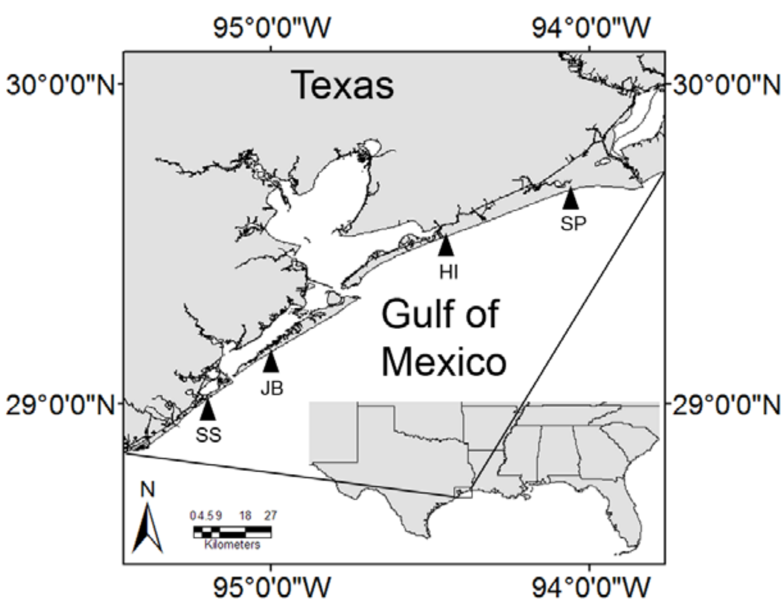

Fig. 3.1. Study sites. Location of each study site, titled by nearest municipality.
SP- Sabine Pass; HI- High Island, JB- Jamaica Beach; SS- Surfside Beach.

Table 3.1. Study sites. Physical description of each study site. Traffic: low = cars within 1 km <5; moderate (5- 10 cars within 1 km of site). High = < 10 cars within 1km. All sites peak in summer.

Site	Longitude/ Latitude	Slope	Beach Energy/ Waves	Grain size	Dunes	Traffic	Use
Sabine Pass	29° 39.760'N; 94° 05.293'W	Low	Low	Fine, some shell hash; seasonal	Low – marsh adjacent	Low-moderate	Fishing; seasonal recreation
High Island	29° 32.969'N; 94° 23.284'W	Mod	Low	Moderate - coarse, clay; seasonal	Impounded sargassum	Moderate	Fishing; seasonal recreation
Jamaica Beach	29° 10.892'N; 94° 58.345'W	Low	Low	Very fine, some shell hash	Established 2004, Panicum stabilized; Fig. 3.2	Low-moderate	Recreation; fishing
Surfside Beach	29° 01.566'N 95° 11.297'W	Low	Low	Very fine	Low- prairie adjacent	Low	Fishing

Fig. 3.2. Jamaica Beach dunes. Photo of dune stabilization and sand fence on the dunes in Jamaica Beach, Texas. Note the linear planting of *Panicum* sp. (bitter panic grass).

Surveys along the upper Texas Coast were taken monthly from July 2007 to May 2009. Geological samples were taken during the summer and winter of each year and within 2 weeks after Hurricane Ike (August 2007, December 2007, July 2008, September 2008, and December 2008). Monthly elevation surveys were conducted at each site from an established benchmark to relative sea level at the time of survey. Field collection was coordinated with the spring tide of each month with sampling occuring within 10 days of the full moon. Benchmark elevation was established and normalized through the nearest NOAA buoy Galveston Pleasure Pier, TX Station ID: 8771510 for Jamaica Beach, High Island, and Sabine Pass site and NOAA buoy, USCG Freeport, TX Station ID: 8772447 for Surfside Beach. Profile data was collected as described by Emery (1961) for each survey, noting high tide line, presence and composition of wrack lines, and location of dune line at each site.

Samples, 10 cm diameter x 10 cm length sediment core, for determining grain size were collected during the summer and winter of each year and after Hurricane Ike. In 2007 three grain size samples were taken at each beach at the -1, 0 and 1 stations. In 2008 three samples were taken at each site at the -5, 0, 5 stations. For seasonal comparisons only the data from the 1, 0, -1 station was used. Sediment was dried in a Thelco, Precision Scientific oven at 35°C (95°F) until at a constant weight was reached (ASTM, 2002; Eleftheriou and McIntyre, 2005). A randomly selected subsample (25 g) was placed in the RO-TAP Testing Sieve Shaker, WS Tyler Company for 15 minutes. This separated the sample by sieve size for final weighing. Six sieves were selected following the procedures established by ASTM (2002) and previous methodologies described by Gray (1981) and Eleftheriou and McIntyre (2005):

No.	Size	Phi	Wentworth size class (1924)
10	2.0 mm	-1	Pebble/ gravel/ granule
40	0.6 mm	.6	Coarse sand
60	0.25 mm	2	Medium sand
120	0.125 mm	3	Fine sand
230	0.063 mm	4	Very fine sand
Tray	> 0.063 mm	>4	Silt and clay

Various physical measurements were taken during each collection period included: salinity, temperature (water and air), wind speed/direction, tide, swash length, and weather conditions. Wave height and wave period were observed both from shore and taken from Buoy 42035 located east of Galveston, Texas maintained by the National Data Buoy Center; buoy data was averaged over a 24 hour period.

There are many indices that have been proposed to physically define beaches. They are commonly described as beach indices or morphodynamics. McLachlan and Brown (2006) recommended four indices to "characterize the beach type". They included:

- Dean's Parameter (Ω) = H/ W*T
- Relative Tide Range (RTR) = TR/H_b
- Beach Index (BI) = $\log_{10}$ (grain size * Tide/ slope)

- Slope = 1/beach face slope

All indices are dimensionless except for Beach Index (BI). Dean's Parameter (Ω) defines the beach type (reflective, intermediate, dissipative), measuring the ability of waves to move beach sediment. Reflective is a steep eroding beach while dissipative is the flat beach state. Dean's Parameter is calculated from the average wave beaker height (H_b), wave period (T) and sandfall velocity (W) (Short and Wright, 1983). Using the values given in Gibbs et al. (1971), sandfall velocity was estimated from the median sediment grain size. Relative Tide Range (RTR) is the measure of waves and tides influence on the shoreline using the tidal range (TR) and average wave breaker height (H_b) (Wright and Short, 1984; Masselink and Short, 1993). Beach Index (BI) is a comparison measure for beaches combining measurements of slope, sediment grain size, and tides (McLachlan and Brown, 2006).

Histograms and simple statistics were conducted using Microsoft Excel 2007. The three subreplicates from each core sampled were averaged before analysis. Skewness, Kurtosis, and sorting were all determined using GRADISTAT, Folk and Ward (1957) method in Microsoft Excel 2007.

3.3 Results

Two summer and two winter sediment measurements were taken over the two year period plus the post Hurricane Ike sampling for each site (Table 3.2). Measurements taken include water temperature, salinity, wave height, wave frequency, slope, sediment grain size. During the two year period, water temperature ranged from 10-34° C, dropping in temperature seasonally. Observable wave height ranged from 0.1 m - 1.2 m. Observable wave period was much more fairly consistent from averaging around 6-7 sec, but ranged from 4-8 sec. The mode sediment grain size varied from 63 to 6000 µm with the highest grain sizes occurring at the highly erosional study site, High Island. Slope remained low across all beaches ranging from 0.63° to 3.27°. Using these factors it is possible to determine beach type for comparative measurements through the described beach indices.

Table 3.2. Physical measurements taken from each survey site along the upper Texas coast. * = measurement not taken. These measurements allow for characterization of beach type. Beach type codes are as follows: R:LTR = Reflective: low tide Terrence with rip tides; I = Intermediate; I:B&R = Intermediate: bar and rip; D:NB = Dissipative: non-barred; UD = Ultra-Dissipative.

Sabine Pass	**Wave height (cm)**	**Grain size (μm)**	**Deans Parameter (Ω)**	**Slope**	**RTR**	**BI**	**Beach Type**
Summer 2007	38	171	6.64	1.5	3.17	2.49	D:NB
Winter 2007	512	178	35.94	1.83	0.30	2.71	D:B
Summer 2008	35	304	2.11	2.3	3.45	2.93	I
Post-Ike 2008	81	695	1.93	1.46	4.29	3.55	R:LTR
Winter 2008	129	133	28.65	1.28	1.24	2.44	D:NB
High Island							
Summer 2007	38	334	2.29	2.59	3.17	3.02	I
Winter 2007	512	757	5.79	2.74	0.30	3.51	D:B
Summer 2008	35	391	1.54	3.26	3.45	3.19	R:LTR
Post-Ike 2008	33	shale	n/a	1.18	10.53	n/a	n/a
Winter 2008	129	368	6.56	0.76	1.24	2.65	I
Jamaica Beach							
Summer 2007	61	121	13.94	1.85	1.97	2.43	D:B
Winter 2007	107	145	16.87	2.42	1.46	2.74	D:B
Summer 2008	29	128	6.27	2.37	4.16	2.56	D:NB
Post-Ike 2008	30	152	2.58	1.63	11.58	2.93	I:B&R
Winter 2008	33	160	6.59	0.85	4.86	2.34	D:NB
June 2009	41	130	9.77	1.51	2.80	2.35	D:B
Surfside Beach							
Summer 2007	61	121	13.94	1.29	1.84	2.24	D:B
Winter 2007	107	147	16.89	1.64	1.28	2.52	D:B
Summer 2008	29	129	6.19	1.68	3.98	2.40	D:NB
Post-Ike 2008	81	156	11.46	0.93	2.82	2.52	D:B
Winter 2008	41	150	9.53	0.87	3.80	2.31	D:NB

McLachlan and Brown (2006) provided a simple interpretation of beach morphodynamic data. Each index was defined as follows: Dean's (Ω) = <2 for reflective, 2-5 intermediate, > 6 for dissipative; Slope = 5.57 degrees for steep reflective, 0.6 degrees for very dissipative; RTR = <3 wave dominated, 3-12 tide modified beaches,

>12 tide dominated beaches; BI = 0 coarse sand, small waves and tides, 4 fine sand, large waves and tides. Combining the indices provided a better interpretation of the beach type (Table 3.3). Using these indices it was determined that the southern study sites (Jamaica Beach and Surfside Beach) could be described as dissipative, tide modified, except for the time period just after Hurricane Ike. These sites were also typically identified as mid-range regarding the Beach Index. The Sabine Pass study site and High Island site post Hurricane Ike did not fit in any generalizations. They were characterized as reflective, intermediate, and dissipative without regard to seasonality or conditions.

Table 3.3. Beach type as defined by the use of Dean's Parameter and the Relative Tide Range. (Short and Wright 1983; Wright and Short 1984; Masselink and Short 1993; Short 1999; Bird 2008)

	Deans Parameter (Ω)	Relative Tide Range
Reflective	<2	<3
Reflective: low tide terrace w/rip	<2	3-7
Reflective : low tide terrace w/o rip	<2	>7
Intermediate:	2-5	<7
Intermediate: bar and rip channels	2-5	>7
Dissipative: barred	>5	<3
Dissipative: non-barred	>5	<7
Ultra-dissipative	>5	>7

In 2007 samples taken along the intertidal stations (1, 0, -1) results were similar (Table 3.4). In 2008 there was some disparity between the stations (5, 0, -5) as samples were located outside the immediate swash zone and typically either entirely subtidal at the time of sampling or out the upper swash zone. Grain size distributions at Jamaica Beach and Surfside Beach showed seasonality (Table 3.4). Hurricane Ike caused all the sites to increase in sediment grain size, but grain size returned to their normal winter value by December with the exception of High Island. During the 2007 winter season, smaller sediment sizes were removed to offshore sandbars. At the High Island site erosion left behind large cobbles and shells. After Hurricane Ike large cobbles and shells and all grain sediments were removed from the High Island beach face. Sands returning to the beach after the hurricane were most likely from the sandbars created by Ike. Variety of sand grains could be explained in the sorting (Table 3.4). Both High Island and Sabine Pass expressed poorly sorted sediments. Jamaica Beach, Surfside Beach, and Sabine Pass experienced moderately to moderately well sorting, sand grains similar. Sorting, Skewness and Kurtosis number ranges are defined in Table 3.5.

Table 3.4. Mean sediment grain size from each study site along the upper Texas coast. Skewness, kurtosis, and sorting included values at the 0 station. * = unable to calculate.

Sabine Pass	**1 (5) (µm)**	**0 (µm)**	**-1 (-5) (µm)**	**Skewness**	**Kurtosis**	**Sorting**
Summer 2007	2.634	2.543	2.526	-0.157	2.363	0.843
Winter 2007	2.474	2.488	2.490	-0.104	1.672	0.630
Summer 2008	2.528	1.720	2.112	-0.526	1.096	1.430
Post-Ike 2008	n/a	0.524	n/a	0.408	0.580	1.759
Winter 2008	2.235	2.911	2.848	0.123	0.754	0.635
High Island						
Summer 2007	2.649	1.583	1.541	-0.521	0.701	1.889
Winter 2007	-0.112	0.402	-0.046	0.372	0.571	1.567
Summer 2008	-1.243	1.353	shale	-0.431	0.662	1.389
Post-Ike 2008	n/a	shale	n/a	*	*	*
Winter 2008	1.172	1.443	0.991	-0.270	1.159	2.086
Jamaica Beach						
Summer 2007	3.079	3.049	3.537	-0.151	0.754	0.640
Winter 2007	2.785	2.790	2.776	0.189	0.918	0.637
Summer 2008	2.986	2.966	2.801	-0.182	0.971	0.754
Post-Ike 2008	n/a	2.722	n/a	0.128	1.199	0.644
Winter 2008	2.496	2.648	0.926	0.165	2.509	0.975
June 2009	n/a	2.940	n/a	0.233	1.304	0.932
Surfside Beach						
Summer 2007	3.016	3.052	3.024	-0.108	0.747	0.621
Winter 2007	2.793	2.771	2.791	0.224	0.905	0.606
Summer 2008	2.945	2.959	3.046	0.016	0.738	0.630
Post-Ike 2008	n/a	2.685	n/a	0.123	1.275	0.622
Winter 2008	2.715	2.740	2.629	0.326	1.243	0.624

Table 3.5. Sorting, skewness, kurtosis table. Folk and Ward (1957) logarithmic method based on ϕ.

Sorting		Skewness		Kurtosis	
Very well sorted	< 1.27	Very fine skewed	0.3 to 1.0	Very platykurtic	< 0.67
Well sorted	1.27 – 1.41	Fine skewed	0.1 to 0.3	Platykurtic	0.67 – 0.90
Moderately well sorted	1.41 – 1.62	Symmetrical	0.1 to -0.1	Mesokurtic	0.90 – 1.11
Moderately sorted	1.62 – 2.00	Coarse skewed	¯0.1 to ¯0.3	Leptokurtic	1.11 – 1.50
Poorly sorted	2.00 – 4.00	Very coarse skewed	¯0.3 to ¯1.0	Very leptokurtic	1.50 – 3.00
Very poorly sorted	4.00 – 16.00			Extremely leptokurtic	> 3.00
Extremely poorly sorted	> 16.00				

Sediment grain size histograms demonstrated the distribution of sand particle size. Visual observations of histograms along with the descriptive statistics of skewness, kurtosis, and sorting assisted in characterizing the environment. These analyses demonstrated seasonal grain size distribution and the disruption caused by Hurricane Ike (Fig. 3.3). The southern and finer grain size study sites showed distinct summer versus winter seasonality histograms. At these sites Hurricane Ike caused the grain size distribution to look similar to the winter season. The distribution at Jamaica Beach in December after Hurricane Ike was slightly different from the previous winter. This was attributed to the constant human manipulation of the beach face. The sediment at Jamaica Beach and Surfside Beach was fairly similar as they were moderately to moderately well sorted, not dependent on season (Table 3.4). Distribution based on skewness and kurtosis explained seasonality in 2007 with platykurtic (peaked) and fine skewness toward finer sediments to winter's mesokurtic (normal) and coarse skewness toward the coarser sediments. Unfortunately the summer 2008 data did not show a return to previous 2007 values. The storm change was evident in these values as the site histograms were leptokurtic (flattened) and fine skewness as sediment values were larger than expected at that time of year and smaller sediment sizes were present but not in the extent normally exhibited. The seasonality at Sabine Pass and High Island was not as distinct as in the southern sites. At High Island seasonality was only observed in the skewness. Sorting was consistently poor with the presence of many types of grain sizes. Seasonality was not observed at Sabine Pass in histograms, skewness, kurtosis, or sorting. The disruption post-Hurricane Ike was also observed at the northern sites with larger grain sizes becoming more abundant. Unlike the southern sites, by December 2008 the distributions varied. The High Island site, even though it was eroded to shale after Hurricane Ike, December 2008 histogram was similar to the July 2007/2008. Sabine Pass histogram did not resemble any previous grain size distribution.

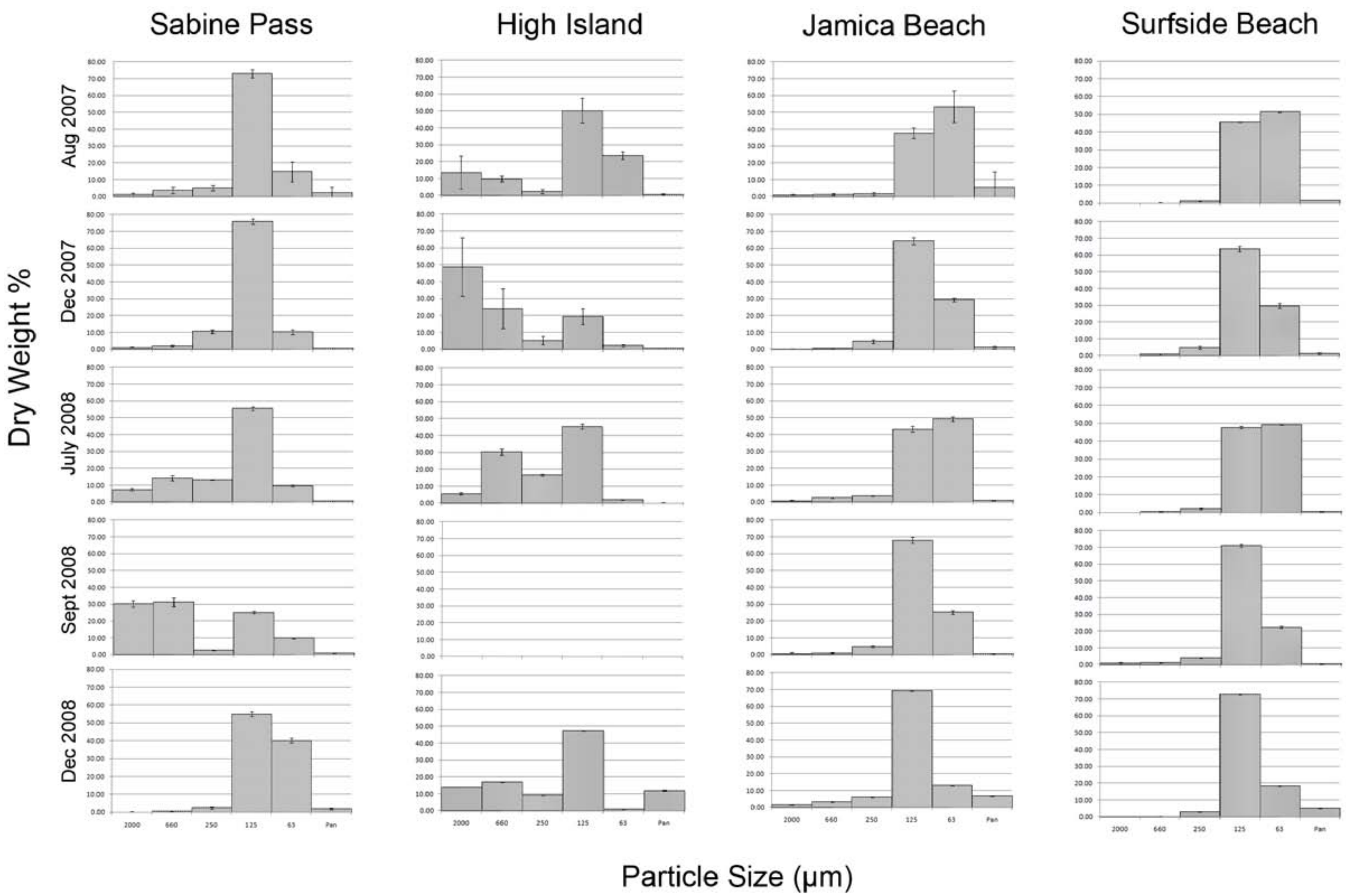

Fig. 3.3. Sediment grain size histograms from study sites along the upper Texas coast.

Beach profiles along the upper Texas were also recorded each month (Fig. 3.4). Upon examining the profiles, using grain size collection dates as reference, seasonality was observed on the southern beaches. The rebound of the summer profiles after the winter was observed. This was not observed in the northern erosional site profiles. Profiles taken after the initial sampling on the northern beaches were depressed as observed at High Island (Fig. 3.4, App II). Little oscillation depicting seasonality was observed at Sabine Pass. Hurricane Ike greatly changed the profiles and elevation at each study site. The profile taken after Hurricane Ike in September 2008 was flatter and more depressed than each of the previous beach profiles. Recovery was observed at each of the sites to varying effects. The northern sites experienced sediment accretion with Sabine Pass fully recovering to summer 2007 levels by May 2009. The southern sites progression after Hurricane Ike varied. At Jamaica Beach, recovery slowed and reversed in the December as human manipulation and beach cleaning was conducted at the beach site. By May 2009 sediment levels were just below winter 2007 levels with slope improving. The Surfside Beach site had a different recovery experience. Hurricane Ike flattened the beach with erosion along the upper beach and accretion in the intertidal zone. Each month after the hurricane the site continued to experience a profile slope decrease because of continued human interference.

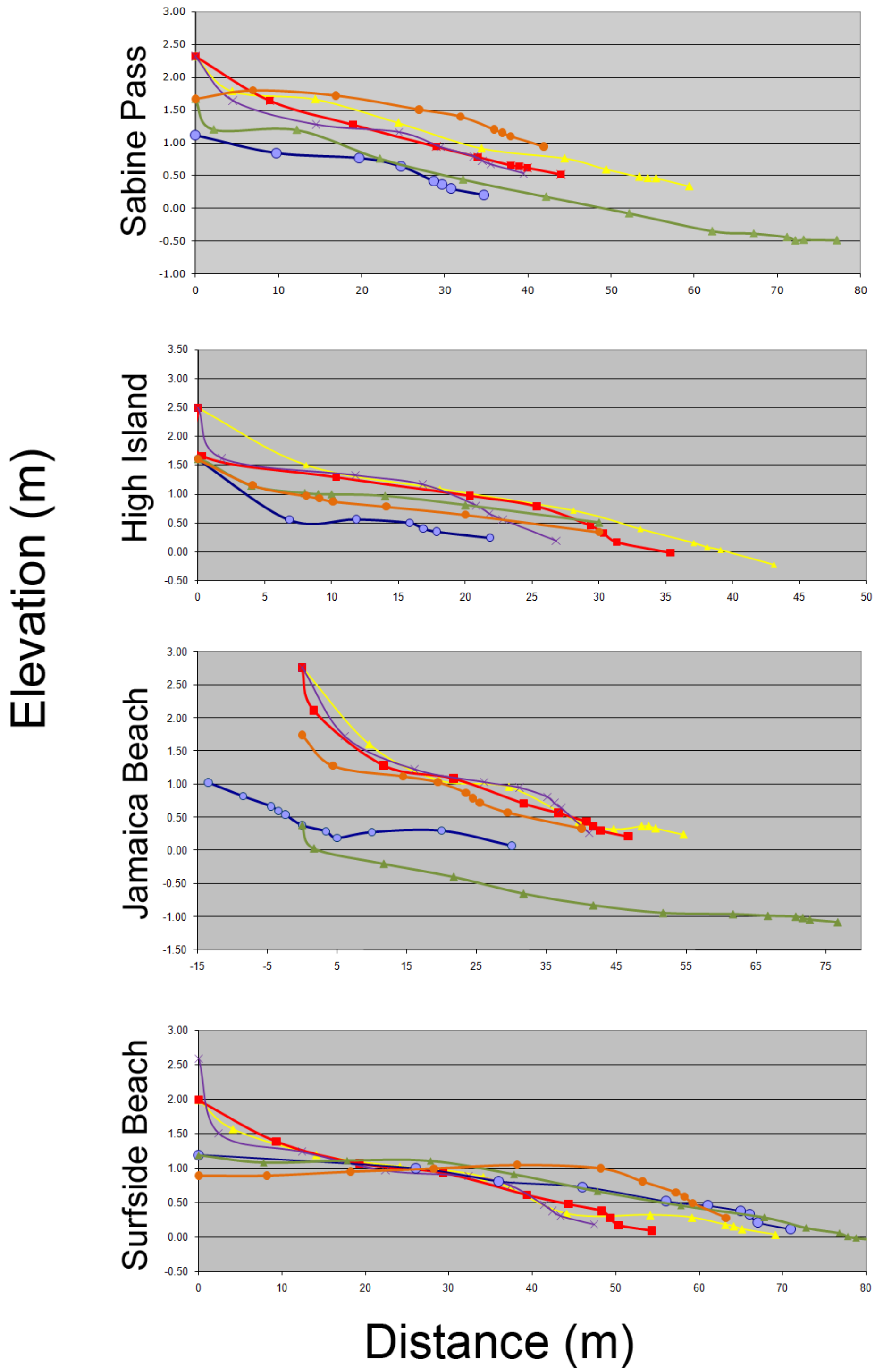

Fig. 3.4. Beach elevation profiles from study sites along the upper Texas coast. Yellow triangle = August 2007; Red square = December 2007; Purple X = July 2008; Blue open circle = September 2008 (post-Hurricane Ike); Green triangle = December 2008; Orange circle = May 2009.

3.4 Discussion

Beach morphodynamics characterizes beach types through the use of beach profile data and shore processes (Bird, 2008). Dean's parameter, based upon a dimensionless fall velocity, Relative Tide Range, and Beach Index are commonly used indices in sandy beach studies (Degraer et al. 1999; Short 1999; Brazeiro 2001; Defeo and Rueda 2002; McLachlan and Dorvlo 2005; McLachlan and Brown 2006; Bird 2008). Generally speaking the upper Texas coast is described as a dissipative. Dissipative beaches have been characterized as low sloping, high wave height, and fine grain size beaches, alternatively reflective beaches are described by steep slopes, low waves, and coarse grain size. (Short 1999; McLachlan and Brown 2006). Although the study sites did not fall within the strict description of dissipative beaches, their name originates from the wide beaches with waves that "dissipate their energy" along the low sloping swash of which the upper Texas coast could be defined (Guza and Inman, 1975; Short 1999).

3.4.1 Seasonality

Open sandy beaches in sediment equilibrium undergo summer-winter seasonal changes of accretion and erosion (Britton and Morton 1989). This was observed through a wide, low sloping summer beach with small sediment grain size followed by winter's steeper, narrower beach with larger grain size. Surfside Beach and Jamaica Beach were observed to experience the summer-winter seasonal changes. The observed slope and profiles on the summer study sites was flatter and wider beach with higher elevation. Although in seasonal equilibrium, the second summer observations did not show an exact return to the previous state. Instead observed site profiles were slightly more depressed with a slope flatter than the observed summer profiles of 2008 (Table 3.2; Fig 3.4). The northern study sites did not experience the same seasonal oscillation observed in the southern sites. Both the Sabine Pass and High Island study sites showed a continued degradation of elevation. Sabine Pass profiles did not exhibit any discernable pattern. High Island was the most erosive site studied and profiles observed continued to degrade each month. This continued degradation of beaches is expected on an eroding coast.

Bullard (1942) described the upper Texas coast with a grain size of 125 µm or smaller. This observation was found to be compatible with current conditions. Sediment grain size was larger on the headlands than on the barrier islands. These northern study sites from Sabine Pass to Rollover Pass were noted to be highly erosional (McGowen et al., 1977; Morton, 1997). The shallow sediment depth and coarse grain size is a feature of this region. On highly erosional beaches waves remove the smaller sediment grain size. Winter sediment size at High Island was very large as only cobbles remained on the upper beach. The upper beach was covered in large shells and cobbles gradating down to crushed shell hash in the swash zone. Hurricane Ike increased sediment grain size at every site. By December much of the grain size distribution returned to near previous winter distribution, except at High Island. The cobbles that were previously present year round were removed from the beach face by the hurricane. Sediment grain size distribution at High Island in December was beginning to reflect the distribution found during the previous summer.

3.4.2 Post-Hurricane Ike

There was a significant loss of sediment after Hurricane Ike, examined in Chapter V. Hurricane Ike caused sediment grain size to increase at least one Wentworth size class (Wentworth, 1922). One half meter of sediment was lost vertically at each beach except for Surfside Beach. The sediment accretion along the lower beach face at Surfside Beach could be from updrift beaches or the San Luis ebb-tidal delta (Morton et al., 1995). Exposed shale/bedrock (cohesive clay) was observed after Hurricane Ike at both Sabine Pass and High Island. The Sabine Pass study site's beach sediment was absent 37 m from the benchmark/previous dune line by a few meters, a narrow strip of shale/bedrock was exposed. In comparison the High Island site experienced shale exposure over the entire intertidal and into the subtidal over 40 m. This exposure lasted several months. Exposure of shale in the subtidal zone at High Island continued through the end of the study even after the sand began returning to the beach face. Uncovered shale was not uncommon on High Island as it was observed in the lower swash zone seasonally during the winter months. Only a thin veneer of sediment on High Island returned after Hurricane Ike as the sampling stations had a few centimeters of sand covering the shale. After the hurricane a full 10 cm set of 12 sampling cores was not obtained during any month at High Island. Sediment grain size at Sabine Pass and High Island did not represent any previous seasonality distribution. Surfside Beach and Jamaica Beach sediment grain size was representative of the previous winter distribution.

Slope was depressed and flattened at each study site. The removal of sediment from the beach face was apparent thorough the changes in elevation and observed nearshore sandbars which were not present before Hurricane Ike. Near many of the sites, scouring from waves and subsequent flooding could be observed in the back dune area where plants continued to anchor the sediment (Fig. 3.5).

Geomorphological recovery to previous a state after the hurricane was apparent at some sites. The Sabine Pass study site located remotely was not subjected to human pressures and manipulation during recovery. Because of being “left alone”, it experienced the quickest natural recovery compared to the other sites. Sediment grain size, elevation, and slope showed positive signs of recovery. Elevation and slope recorded at the last sampling (May 2009) reflected summer values of 2007. Along the study sites at High Island and Jamaica Beach, sand was dumped at the “new” upper beach face to prevent continued erosion and to protect the road and houses, respectively. Jamaica Beach continued to experience human pressures as the beach sediments were leveled, sifted and replaced for safety and in preparation for spring/summer tourism. The study site at Surfside Beach underwent heavy human pressures as the road paralleling the beach just behind the site was washed out for about 2 km. This site, which before Hurricane Ike experienced moderate fisherman traffic, became the road for passage and reconstruction. Bulldozers, large diesel trucks, construction equipment and residential vehicles were observed traveling along the beach until a new road was completed in April 2009, eight months after the hurricane. These extreme pressures also observed in the data as the compaction continued to flatten this beach.

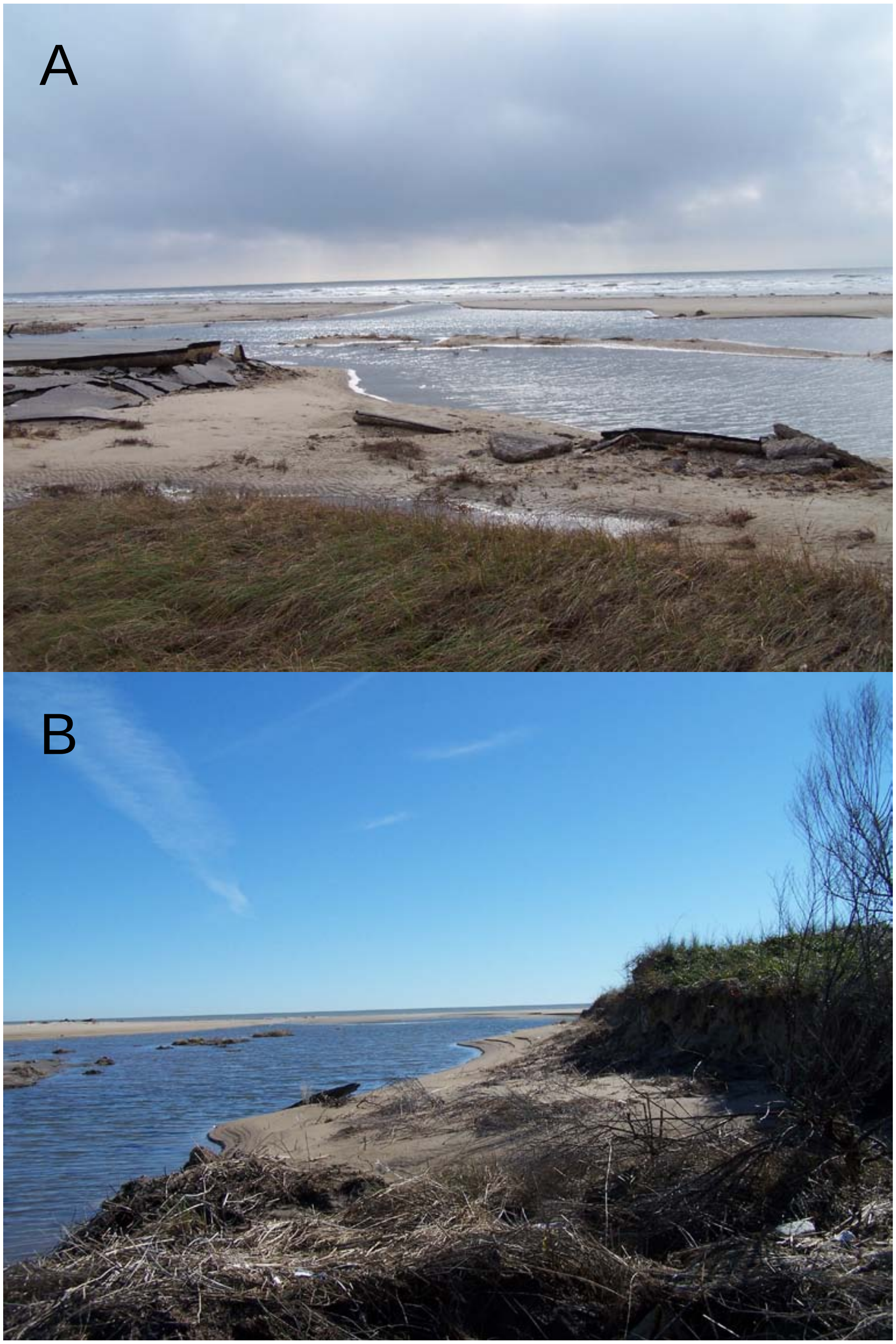

Fig. 3.5. Examples of back dune scour from Hurricane Ike. Photos were taken outside Surfside Beach, Texas (a) and at Sea Rim State Park, near Sabine Pass, Texas (b).

3.4.3 Conclusion

The geomorphology of the upper Texas coast is in a continuous progression of erosion and landward retreat. Continued erosion, increasing storm intensity, and sea-level rise will change and modify the land-sea interface resulting in a change of the coastline. Erosion of open sandy beaches is a natural progression of the mobile shorelines, removing sediment from the upper beach and dunes to the intertidal zone and beach face. With many dunes backed by hard structures, the natural progression may change the state of Texas's beaches from a wide gentle sloping beach to one that may be narrow and steep (Pilkey and Wright, 1988; Kraus and McDougal, 1996; Fletcher et al., 1997; Morton, 1997; Griggs, 2005a). As coastal retreat progresses several study site profiles may be altered as they are backed by hard structures such as roads, embayments, and other means as land owners attempt to hold back the sea.

The findings in this study confirmed that erosion and modification of the upper Texas coastline by both short term hurricanes (pulse events) and the longer term process of waves, tides and subsidence continue to modify this naturally mobile coastline. The future of this coastline will vary dependent upon the amount of human alteration. The request for hard structures to protect homes and roadways could "terminate" the island and coastline from the natural erosion process (Stutz and Pilkey, 2005). This resulting dilemma of saving the coastline in its current position or allowing it to progress naturally is a continued debate of stakeholders and conservationists.

Supplemental data on Texas beach morphodynamics may be found in Appendix B.

CHAPTER IV

ECOLOGY OF SANDY BEACH INTERTIDAL MACROFAUNA ALONG THE UPPER TEXAS COAST

4.1 Introduction

Ecological studies of sandy beaches have been conducted on a variety of beaches worldwide (Shelton and Robertson, 1981; McLachlan et al., 1981; McLachlan, 1990; Degraer et. al, 1999; Jackson et al., 2002; McLachlan and Dorvlo, 2005; Rodil et al., 2006; Speybroeck et al., 2008). Many studies have attempted to quantify and qualify beaches and their interactions with organisms and disturbances both natural and manmade (McArdle and McLachlan, 1992; McLachlan et al., 1993; Peterson et al., 2006). Unfortunately many of those studies were one time surveys either sampling only in the summer or obtaining a summer and winter sample. Studies with repeated seasons are necessary to draw conclusive analyses. Monthly and repetitive seasonal sampling on a beach is both time intensive and difficult to maintain.

With coastal retreat, sea-level rise and increasing human pressures, beach ecosystems are in need of examination. Schlacher et al. (2007) identified several directions for future research on beach ecosystems to enhance management and conservation issues. Particularly of interest was that beach ecosystems need seasonal baseline data along with the geomorphological relationship to better understand future possible changes. Sandy beaches are vitally important as an ecosystem and for coastal communities (Small et al., 2000; Micallef and Williams, 2002; Davenport and

Davenport, 2006; Feagin et al., 2005; Schlacher et al., 2007). Better management and increasing conservation dictates that more research is necessary to assess the increasing loss of this habitat type. Texas beaches are experiencing an average loss of coastline at the rate of 2 m annually (BEG, 2010). As sea-level rise and coastal retreat continue, immobile developments adjacent to beaches will begin to squeeze the life from this mobile ecosystem. This will cause the future of sandy beaches to be uncertain (Schlacher et al., 2007).

This study examined the temperate upper Texas coast intertidal macrofaunal ecology. The upper Texas coast experiences summer, winter and intermediate seasons. During the summer, air and water temperatures average 30 °C in contrast to the average winter temperature of 12 °C (NODC, 2010). The Texas coast experiences tropical storms at the rate of 0.67 annually with hurricanes making landfall once every two years (Hayes, 1967; McGowen et al., 1977). Winter storms called “northers” occur at a rate of 15-20 per year (Hayes, 1965; McGowen et al., 1977; Britton and Morton, 1989). Winter storms are capable of bringing freezing temperatures to Galveston Bay. These storms change the characteristics of the beach, flattening or increasing the slope and sediment grain size. Linking seasonal weather and the geophysical characteristics to the oscillations of macrofaunal patterns may assist in predicting what may come for this region. This study attempted to create a baseline for which further ecological studies along the Texas coast could be built upon.

4.2 Materials and methods

4.2.1 Study sites and design

A two year study of the upper Texas coastal intertidal macrofauna began in 2007. Data in this chapter covered the period from July 2007-August 2008. A large hurricane occurred between the August and September 2008 sampling ending the baseline data set. Data from September 2008-May 2009 will be covered in subsequent chapters. Numerous tropical storms make landfall along the upper Texas coast. Prior to this study the most recent hurricane was Hurricane Rita in 2005. It was the intent of this study to quantify any residual effects from the hurricane, examine seasonality of the intertidal zone and quantify any effects of tropical storms that might occur during the two year period.

Four sites were selected along the upper Texas coast and were named by their nearest municipality. The sites were located at or near Sabine Pass, High Island, Jamaica Beach, and Surfside Beach (Fig. 4.1). The first site was selected based upon landfall of Hurricane Rita (Sabine Pass) with the following three upon distance from the previous site (increasing possibility of tropical storm landfall), low to moderate vehicular use (although this did change at a few sites), and ability to reach the site. Sites were selected for documenting beach zones, sediment size, and macrofaunal densities. Sampling occurred monthly within 10 days of the full moon. The beaches along the upper Texas coast are fairly flat, moderately wide and microtidal, with tides typically no more than 1m.

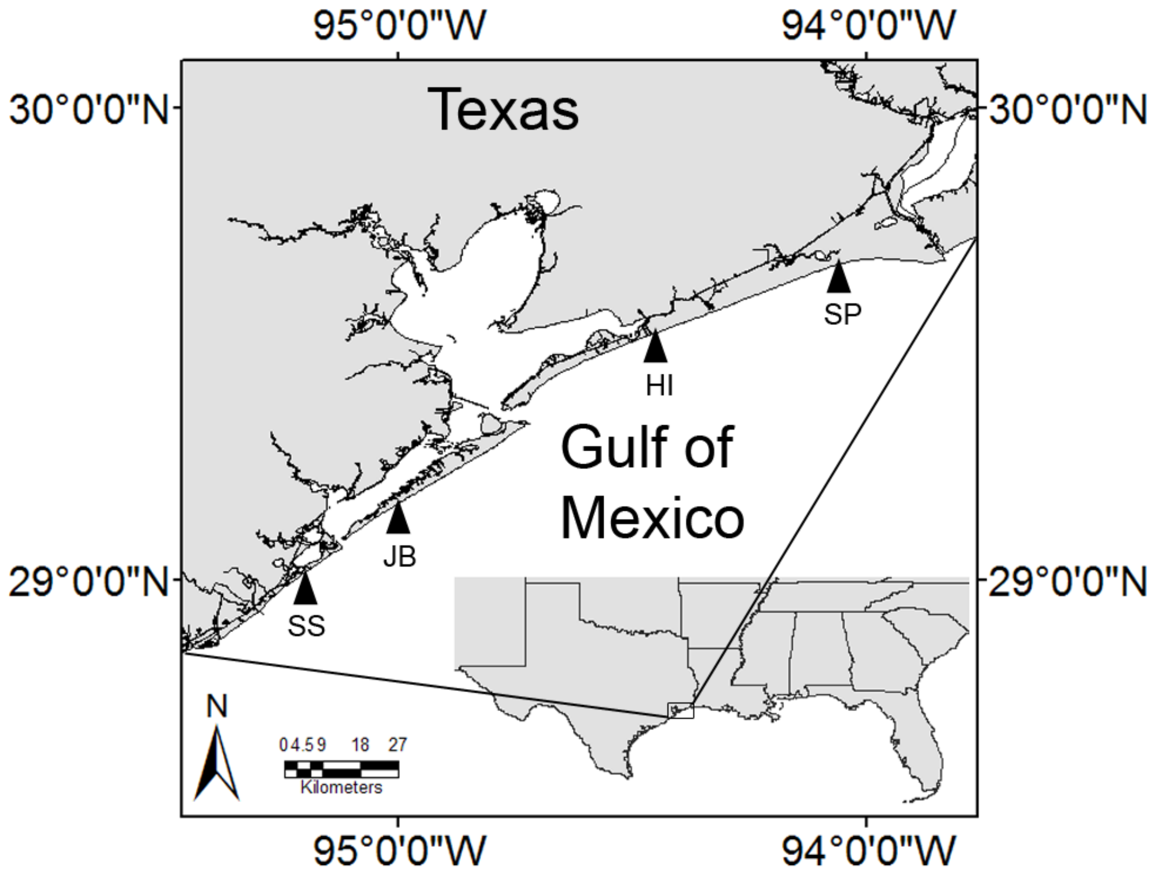

Fig. 4.1. Study sites. Location of each study site, titled by nearest municipality. SP- Sabine Pass; HI- High Island, JB- Jamaica Beach; SS- Surfside Beach.

At each site two intertidal transects were established with one transect extending to the dune line (Fig 4.2). The two intertidal transects were 10 m apart. Stations for sampling were established based on relative sea level at the time of sampling. Relative sea level was determined by the average wave run up. Six stations were set during each sampling period, one subtidal (-5 m), three within the immediate swash (-1 m, 0 or at sea level, and 1 m), one typically just outside the swash (5 m), and one extending into the damp zone (10 m) (following methodology of Moreno, et al., 2006; Boudreau, 1998; Gray, 1981). These stations were positioned to identify any possible zonation of the intertidal macrofauna collected. The extended transect was demarked by a pole or marker that remained for the duration of the study, through August 2008. Elevation measurements were taken along the extended transect using laser survey, LaserMark LMH series. Elevation was normalized to the North American Vertical Datum 1988 (NAVD ’88) using the mean low low water mark (MLLW) verified data from NOAA buoy, Galveston Pleasure Pier, TX Station ID: 8771510 for Jamaica Beach, High Island, and Sabine Pass site and NOAA buoy, USCG Freeport, TX Station ID: 8772447 for Surfside Beach. Observations on the locations of the high tide line, wrack lines (if present), and dune line was noted for each site (following methodology described by Emery, 1961). Physical measurements such as salinity, temperature (water and air), wind speed/direction, wave height (following procedures described in Bascom, 1964), tide, swash length, and weather conditions were also taken at each site. Other data collected included major shell presence, wrack line location(s), debris and any other relevant biota identification/notes.

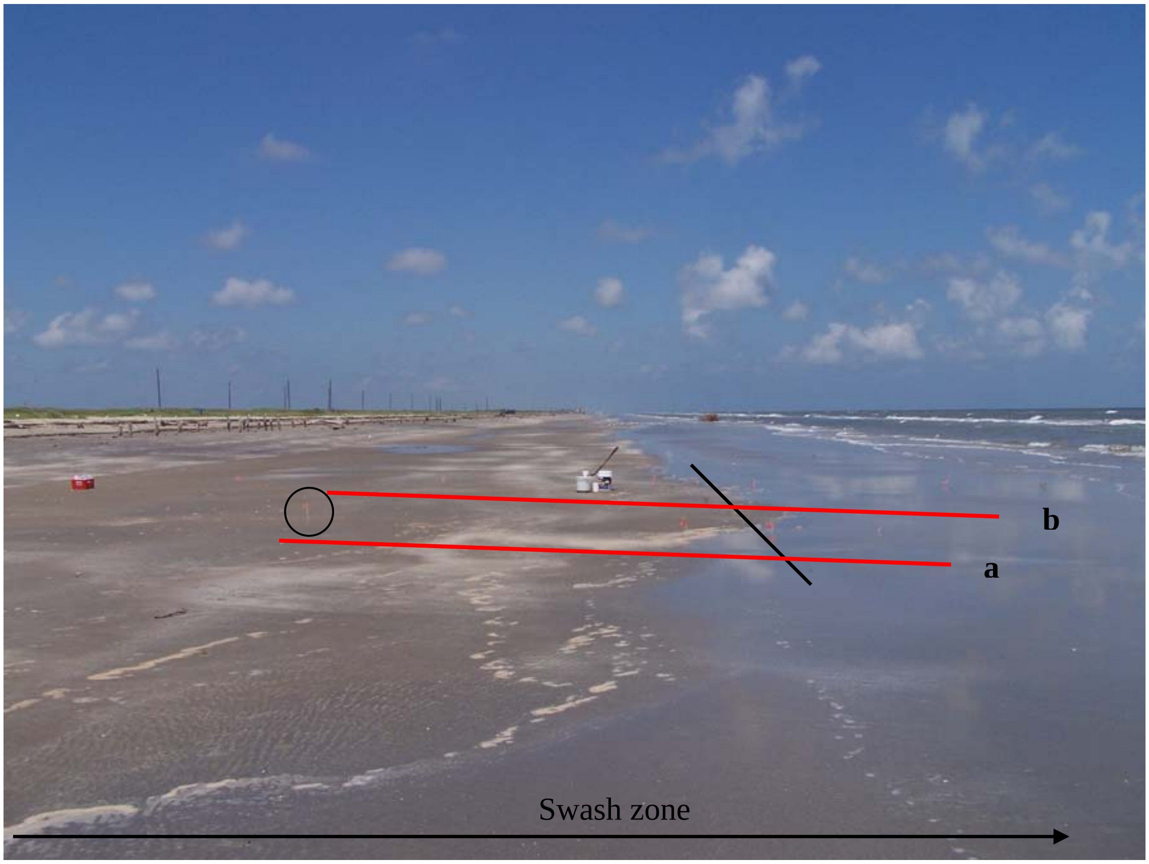

Fig. 4.2. Transect line at Surfside Beach study site. Note the two red lines denoting each transect line, as identified by the orange flag line. One orange flag is circled denoting a.5; 5 m above the 0 station (RSL on that day/time). Black line intersecting the red lines denote the “0” station. Elevation measurements were taken along the “b” line. Example of a summer beach at low tide, note the low gradient and wide swash zone.

4.2.2 Sediment analysis

Sediment was collected during the summer and winter each year from each site and after Hurricane Ike in September 2008, five collections total. Three 10 cm x 10 cm cylindrical cores taken in 2007 were in the swash zone (-1 m, 0 m, 1 m), while those taken in 2008 extended outside the swash (-5 m, 0 m, 5 m). Post Hurricane Ike sample was taken at the 0 m station only. The varied sampling was to determine the similarity of sediments within the beach face at a single site. For consistency the values from the 0 core was used to determine beach type and comparison against macrofauna detected. Sediment was placed in ziplock bags for transport. In the laboratory sediments were dried at 35 °C in a Thelco Precision Scientific oven until a constant weighed was obtained, minimum of three days (ASTM, 2002; Eleftheriou and McIntyre, 2005). A randomly selected 25 g sample was placed on top of six nested sieves for sorting using a RO-TAP Testing Sieve Shaker, WS Tyler Company for 15 minutes. This separated the sample by sieve size for final weighing. Sieves ranged from 2.0 mm to <0.063 mm with each Wentworth size class (1924) represented: 2.0 mm (gravel), 0.6 mm (coarse sand), 0.25 mm (medium sand), 0.125 mm (fine sand), 0.063 mm (very fine sand), < 0.063 mm (silt and clay fraction).

4.2.3 Macrofauna

Intertidal core samples were collected at each station and beach every 4 weeks. Field collection was coordinated with the spring tide of each month with sampling occuring within 10 days of the full moon. A total of 48 cores were collected monthly. Cores were 10 cm diameter x 10 cm length, cylindrical (0.00785 m^2). Total surface area collected monthly was 0.0942 m^2 per site or 0.3768 m^2 total across all sites. Core samples were taken along each transect at the -5, -1, 0, 1, 5, and 10 m stations along each line (following methodology of Moreno, et al., 2006; Boudreau, 1998).

Cores were sieved on site with a 1.0 mm bucket sieve with the retained material on the sieve preserved in 10% formalin and pre-stained with Rose Bengal until sorting in the laboratory at Texas A&M University, College Station, Texas. In the laboratory specimens were sorted from remnant shell fraction and debris, identified and counted. Identified specimens were stored in 95% ethanol (NMNH, 2010). Identification was made to the lowest possible taxonomic level. A list of identified macrofauna and resources used for identification may be found in Appendix C.

4.2.4 Community analysis

In order to fully understand a community, a large amount of sampling must be carried out at the study site. One study site, Jamaica Beach, was selected for a full community analysis. This snapshot analysis examined the intertidal beach in June 2009, ten months after Hurricane Ike. The sampling design followed suggestions given in Schlacher et al. (2008). The design differed from the monthly study in number of intertidal stations and number of shore normal transect lines. Seven stations were evenly spaced per transect from the low swash (station 1) to the wrack line (station 7), 20 m distance. Thirteen shore normal transects spaced 5 m apart extended down the shoreline for 60 m. Ninety-one total cores were retrieved. Coring and preservation followed previous macrofaunal procedures. In addition to the intertidal sampling one transect was extended into the subtidal zone for 70 m with stations every 10 m. information obtained was to verify the presence or absence of intertidal organisms found subtidally. Sediment core was also obtained for grain size analysis at relative sea level (station 3).

4.2.5 Statistical analyses

Diversity measurement analysis was conducted on the benthic survey data. Diversity indices used include richness (S), Shannon-Weiner diversity index (H’) and

Simpson's evenness (E). Analysis was conducted in Microsoft EXCEL with diversity analysis add-in from University of Reading, United Kingdom.

Before conducting any statistical analysis, data were inspected to remove pelagic taxa from the data set. Because of missing (zero) values and lack of normality, non-parametric measures were used for analysis. Kruskal-Wallis tests were used for analyses with Mann-Whitney posthoc. Raw data using both a and b transects was examined. High Island was removed from the site comparison analyses because of significant outlier status. Correlation analysis was conducted using physical measurement and monthly abundance data. Monthly abundance data was pooled over the "b" transect only. Because of rain and cold, some "a" transects were not collected over the 15 month period. A multivariate analysis using the Bray Curtis method was conducted on the benthic survey data to identify patterns of seasonality. Monthly data used the pooled "b" transect data. Square root transformations and Jaccard similarity measures were applied to the data set before each multivariate analysis to counter the effect of absences and rare species in the data set (McCune and Grace, 2002). Jaccard was selected as the best method of analysis because of its ability to handle mutual absences and having better metric properties (Oksanen, 2007). A multivariate data analysis was conducted in PC-ORD. Univariate analyses were conducted using SPSS version 16.0. Means and standard deviations were calculated using Microsoft Excel 2007. Sediment analysis was conducted in Excel 2007, using GRADISTAT. The Folk and Ward (1957) method was employed for sediment sorting, skewness, and kurtosis. Cole rarefaction was conducted using EstimateS version 8.2.0 (Colwell, 2006). P-values were considered statistically significant at 0.05 level. Because of use of non-parametric tests, p-values were considered of statistical interest between 0.1-0.05 level.

4.3 Results

4.3.1 Physical measurements

Several physical measurements were taken every month at each study site. During the study period water temperature ranged from 5.5 °C to 35 °C with a mean of 25.6 °C (SD = 6.2 °C). Air temperature ranged from 9 °C to 33 °C with a mean of 24.3 °C (SD = 6.3 °C); Salinity ranged from 16-33, mean 25.6 (SD = 3.7). Observable wave height ranged from 0-1.2 m, mean 0.5 m (SD = 0.3 m). Swash was measured from highest wave run up of 10 m to greatest pull back of -7 m, mean swash range was 5.6 m, +2.7 m to -2.9 m (SD = 3.0 m, 2.2 m and 2.0 m respectively) . Relative sea level was typically in the middle of this range with slight skew toward the landward direction. Of the physical measurements, only slope differed significantly between sites (p=0.003) (Table 4.1). The slope was greatest at High Island (3.26°) during July 2008. Slope was observed to vary seasonally at Sabine Pass, Jamaica Beach and Surfside Beach with Surfside Beach having the lowest slope grade overall. Sabine Pass in the winter of 2007 was observed to be 0.24° flatter. Slopes at the northern sites (mainland) increased each season, as slopes from the southern sites (barrier islands) experienced a slight return/decrease of slope during the 2008 summer season (Fig. 4.3). Many physical measures were found to be correlated by month such as: study site to location (mainland vs. barrier island), study site to slope, month to salinity, month to slope, water temperature to air temperature, and water temperature to grain size.

Table 4.1. Summary statistics of physical measures at study sites along the upper Texas coast from July 2007 to August 2008 (summer vs. winter). Mean/standard deviation determined for each season: summer included the months June-August; winter included the months of January and February. During the winter survey at Sabine Pass only one month of data was used (February). *= of statistical interest. **= statistically significant.

a.

Study Site **Summer**	Water temp (°C) (mean±SD)	Air temp (°C) (mean±SD)	Salinity (mean±SD)	Waves (m) (mean±SD)	Swash range (m) (mean±SD)	Slope (°) (mean±SD)
Sabine Pass	29.80 ±2.17	30.30 ±3.49	25.30 ±3.77	0.15 ±0.15	3.00 ±1.73	1.85 ±0.39
High Island	29.90 ±2.30	27.70 ±3.27	26.60 ±4.67	0.36 ±0.23	3.50 ±1.32	2.93 ±0.33
Jamaica Beach	29.60 ±1.34	30.60 ±3.36	29.30 ±2.82	0.36 ±0.23	6.67 ±4.16	2.13 ±0.38
Surfside Beach	30.20 ±2.17	29.60 ±1.52	29.50 ±1.87	0.30 ±0.00	5.00 ±3.61	1.54 ±0.26
p-value (df=3)	0.949	0.536	0.353	0.467	0.647	0.003**

b.

Study Site **Winter**	Water temp (°C) (mean±SD)	Air temp (°C) (mean±SD)	Salinity (mean±SD)	Waves (m) (mean±SD)	Swash range (m) (mean±SD)	Slope (°) (mean±SD)
Sabine Pass	17.00	16.00	23.00	0.30	4.00	1.67
High Island	12.50 ±4.95	8.75 ±4.60	25.50 ±0.71	0.61 ±0.00	5.00 ±1.41	2.77 ± 0.12
Jamaica Beach	12.50 ±3.54	12.00 ±1.41	25.00/1.41	0.46 ±0.22	8.00 ±2.83	2.65 ± 0.87
Surfside Beach	14.00 ±2.83	16.00 ±0.00	25.00 ±0.00	0.53 ±0.11	9.00 ±0.00	1.91 ±0.02
p-value (df=3)	0.445	0.166	0.410	0.387	0.245	0.185
p-value between seasons (df=1)	<0.001**	<0.001**	0.075*	0.020**	0.067*	0.268

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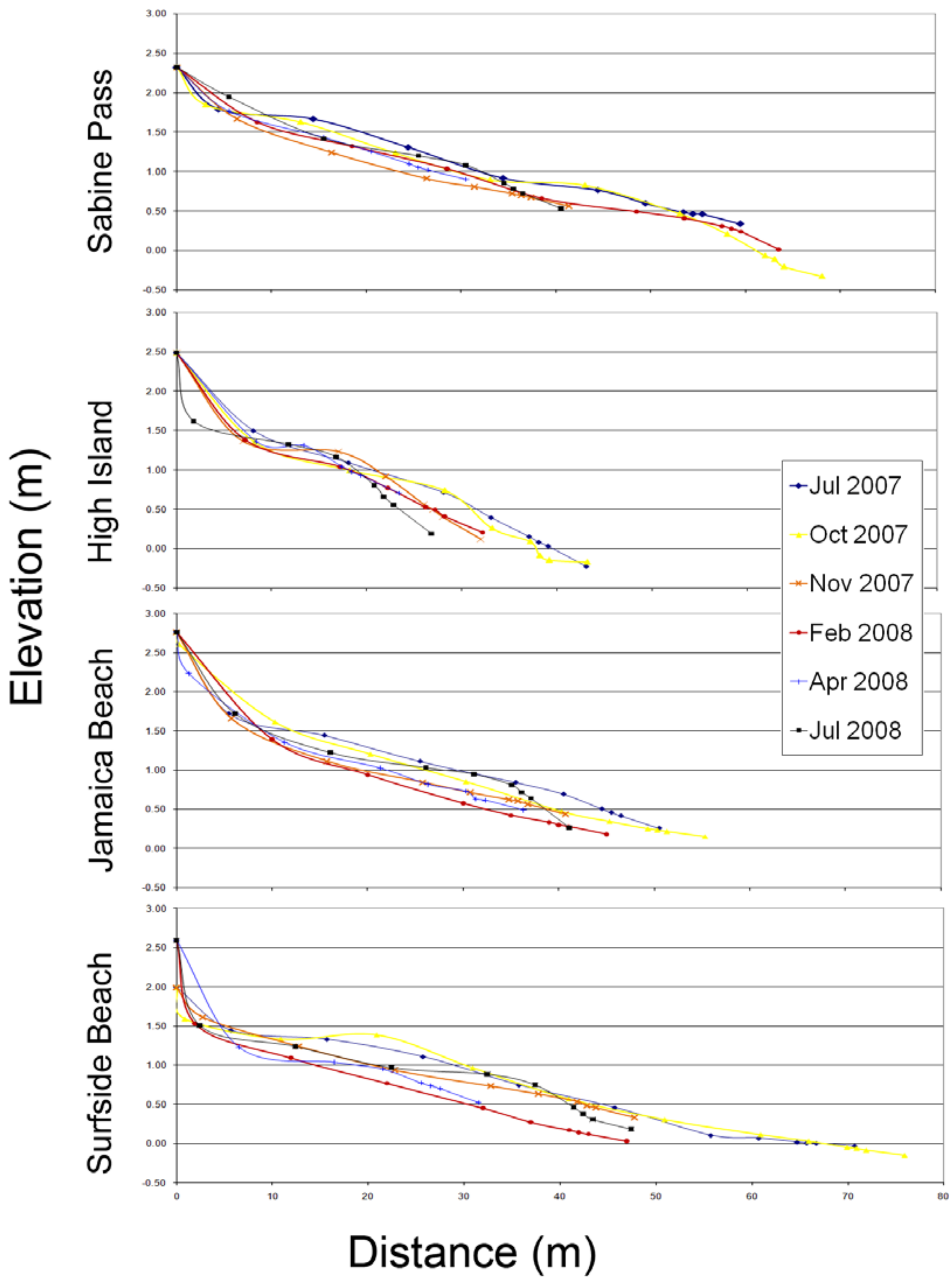

Fig. 4.3. Beach profiles of selected months from the four study sites along the upper Texas coast. Selected months were based upon seasonality as determined from multivariate tests.

4.3.2 Biological composition

During the fifteen month study period 27,639 organisms were collected with 22 benthic taxa identified (Appendix C and D). The six most common and abundant taxa comprised 98% of the total organisms collected. These were the polychaetes *Scolelepis squamata* and *Lumbrineris* sp., amphipods of the family Haustoriidae, the isopod *Ancinus depressus*, the mole crab *Emerita portoricensis*, and the coquina clam *Donax* spp. Two of the top six taxa comprised of 92% of the total benthic organisms counted (*Scolelepis squamata* and Haustoriidae). Examining monthly data (pooled station abundance), study sites were found to be significantly different by abundance as well as the top two taxa, Haustoriidae and *Scolelepis squamata* ($p=<0.001$, <0.001, 0.011 respectively). This was because of the low numbers found at High Island. When High Island was removed the data set, the study sites were no longer statistically significant except for *Scolelepis squamata* ($p=0.281$, 0.543, 0.026 respectively as above). For statistical analyses High Island was removed from the site comparison data set because of outlier site status.

Diversity at each site was low with the highest value of 1.35 (Appendix D). Evenness varied greatly but did not exhibit a noticeable pattern between site/month/station. While some evenness values were high, it was found that only a few taxa were present in those samples. Diversity was observed to be the highest at Surfside Beach and Jamaica Beach during the summer months of June, July, and August at stations -5m and -1m. Although these month/site/station experienced higher richness values it does not necessarily reflect the highest abundance counts, which were typically at the 1m and 5m stations. In a community that is dominated by only a few organisms, these values demonstrate the higher reproductive months. The greater diversity experienced by the lower intertidal zone may include organisms that are swept into the area by wave action.

Overall abundance was observed to increase in the summer and decrease during the winter months (Fig. 4.4). Depressed values such as September (1) 2007 may be an artifact of weather because it rained intermittently throughout the sampling day. Sabine Pass, Jamaica Beach and Surfside Beach all show similar abundance counts, whereas High Island's counts are very depressed. Although summer abundance from the first year to the second was not identical, ordination analysis revealed June, July and August clustering fairly tightly in each axis rotation along with January and February clustering during the winter months (Fig 4.5). Presence of excessive *Sargassum* wrack (> 0.5m height) was observed in the summer of 2007 whereas the summer of 2008 only minor wrack was observed. The presence of an intermediate season was identified in the ordination with the clustering of the months of October and April (Fig. 4.5). Abundance was not similar during these months, but taxa richness, evenness and diversity were slightly similar at a few sites. The two dominant species, Haustoriidae and *Scolelepis squamata*, along with abundance were all statistically significant between these two months (p=0.046, 0.05, 0.050 respectively). The cause of this intermediate season cluster could best be defined in a multi-year study. Months identified for the summer and winter seasons were based on the clustering observed in this ordination.

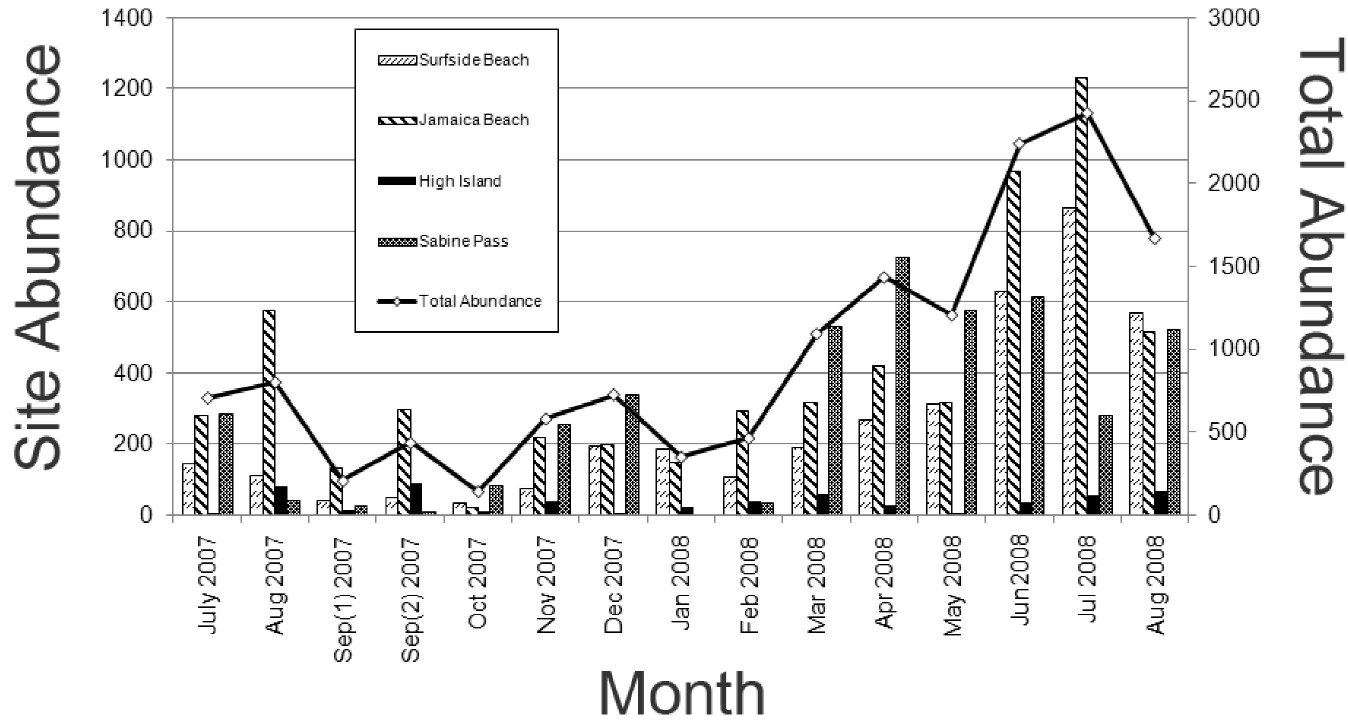

Fig. 4.4. Intertidal macrofaunal abundance across all taxa by month and site along the upper Texas coast. Y axis (bars) denotes site abundance counts. Secondary Y axis (line) denotes total abundance counts over all sites.

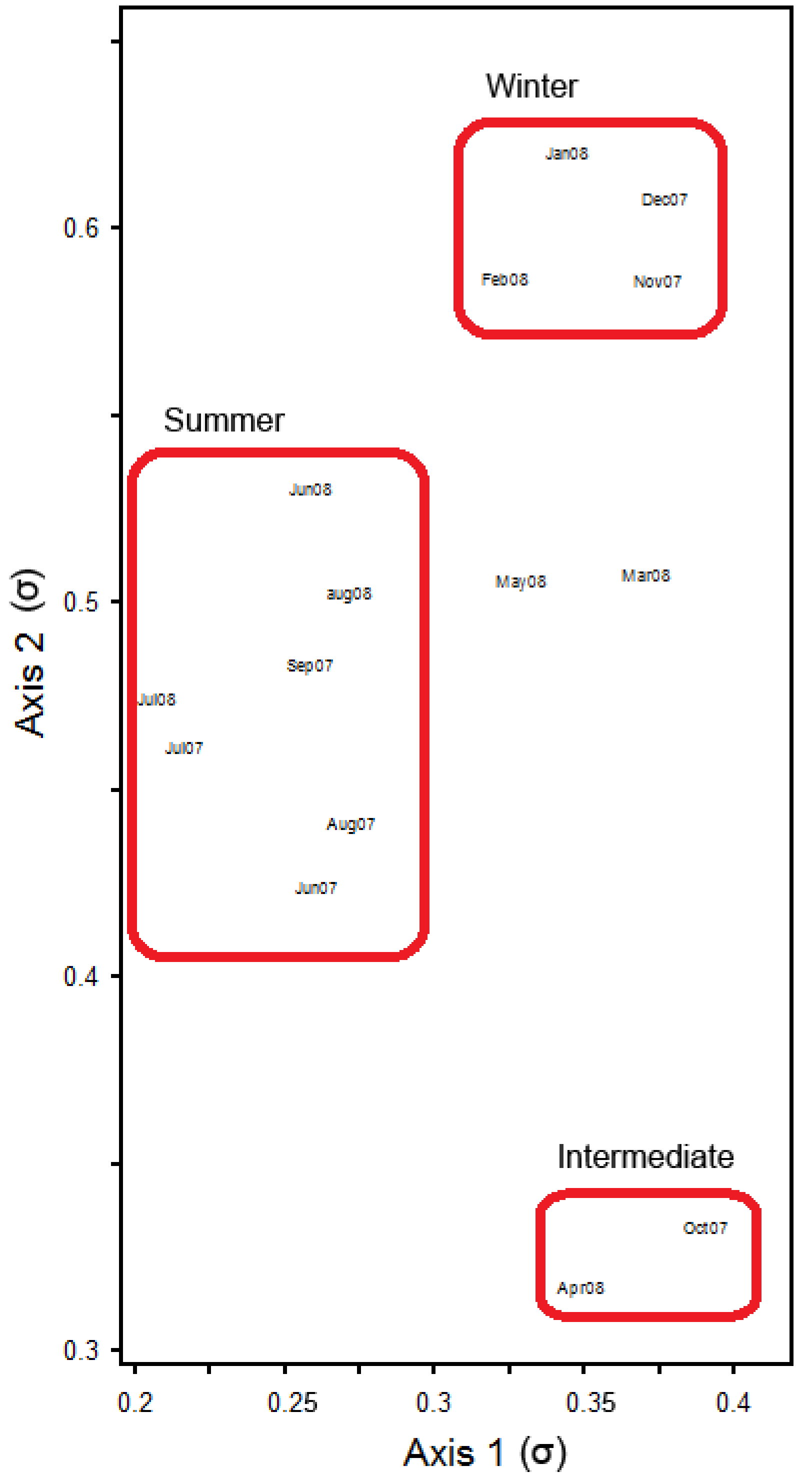

Fig. 4.5. Seasonality defined by intertidal macrofauna abundance along the upper Texas coast. Bray-Curtis similarity ordination with Sorenson measures. Stress = 10.4.

This seasonal abundance oscillation was observed at each site and reflected in taxa (Fig 4.6). Dominance of the top two taxa could easily be observed and their greater abundance can manipulate seasonality. Haustoriidae were observed to increase in abundance during the spring, peaking in early summer. In contrast *Scolelepis squamata* is observed to lag behind the Haustoriidae in numbers peaking in midsummer, retaining numbers longer through the seasons. The other four common taxa showed evidence of seasonality occurring in synchrony with the two dominant taxa. *Donax* shows some evidence of having two reproductive seasons. An increase in *Donax* numbers was observed in late spring (April) and late summer (August). Abundance and taxa across all sites were found to be significant by season with the exception of *Ancinus depressus* which was relatively low in numbers (Table 4.2). Examining individual sites, variations were evident and statistical significance reflected. Low occurrence of organisms at High Island made seasons undetectable.

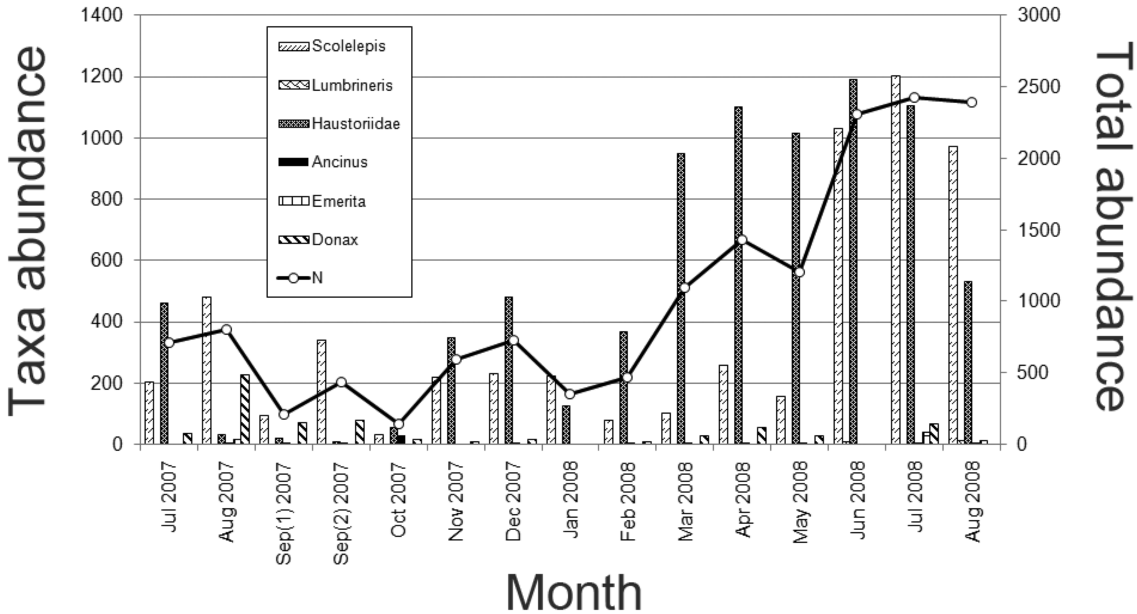

Fig. 4.6. Most common six intertidal taxa abundance by month across all study sites along the upper Texas coast. Y axis (bars) denotes taxa abundance counts. Secondary Y axis (line) denotes total abundance counts over all sites.

Table 4.2. P-values for abundance and most abundant six taxa across seasons. Seasons were as follows: summer = June, July, and August; winter = January and February. Values from Kruskal-Wallis tests on seasonality from raw data. Degrees of freedom = 1. *= of statistical interest. ** = statistically significant.

	N	*Scolelepis*	*Lumbrineris*	Haustoriidae	*Ancinus*	*Emerita*	*Donax*
Overall	0.001**	0.000**	0.018**	0.045**	0.544	0.001* *	0.016**
Sabine Pass	0.006**	0.001**	0.396	0.186	0.134	0.219	0.805
High Island	0.418	0.714	0.237	0.502	0.502	0.120	0.061*
Jamaica Beach	0.004**	0.000**	0.446	0.031**	0.518	0.027**	0.187
Surfside Beach	0.201	0.025**	0.018**	0.049**	0.373	0.029**	0.016**

4.3.3 Zonation

Zonation can be defined using either the presence of organisms or the physical features. In this study, zones were defined by physical features in an attempt to attribute taxa to those zones. As a rule, swash ranged over the -1 m, 0 m, and 1 m stations. The -5 m station was typically underwater during the sampling, while the 5 m was just outside the upper swash. The sand at the 5 m station was wet and slightly compact. The 10 m station was typically located near the high tide mark with damp, hard and compact sand, above the effluent line. As described by McLachlan et al. (1985), the effluent line is the point at which the water table meets the beach just outside the swash. The zones were defined as: low/subtidal intertidal = -5 m; mid-low intertidal/swash zone -1 m , 0 m, 1 m; mid-intertidal = 5 m; upper intertidal zone = 10 m. Statistical significance was found between identified zones later by examining summer variables: total abundance and individually by the taxa *Scolelepis squamata* and Haustoriidae. Stations by season were found to be statistically significant. Pairwise comparison of stations in the winter did not always provide the same statistical significance because counts of animals are lower during the winter season. Stations were found to be statistically significant at different across sites ($p=<0.001$) and by site (SP=0.020, HI=<0.001, JB=0.001) with the exception of Surfside Beach ($p=0.498$). Except for *Scolelepis squamata*, the six most common taxa were found to be statistically significant by station at the 0.001 level or less. *S. squamata* was found to be of statistical interest ($p=0.073$). Overall Haustoriidae were more dominant at the mid-intertidal, with *Scolelepis squamata* dominating the mid-low intertidal, swash zone (Fig. 4.7). *Donax* spp. was found in all zones except for the upper intertidal. Three taxa, *Emerita portoricensis*, *Ancinus depressus* and *Lumbrineris* sp., were located within the swash zone and low intertidal. *Emerita portoricensis* and *Donax* spp. were both found most commonly at the 0 m and -1 m stations.

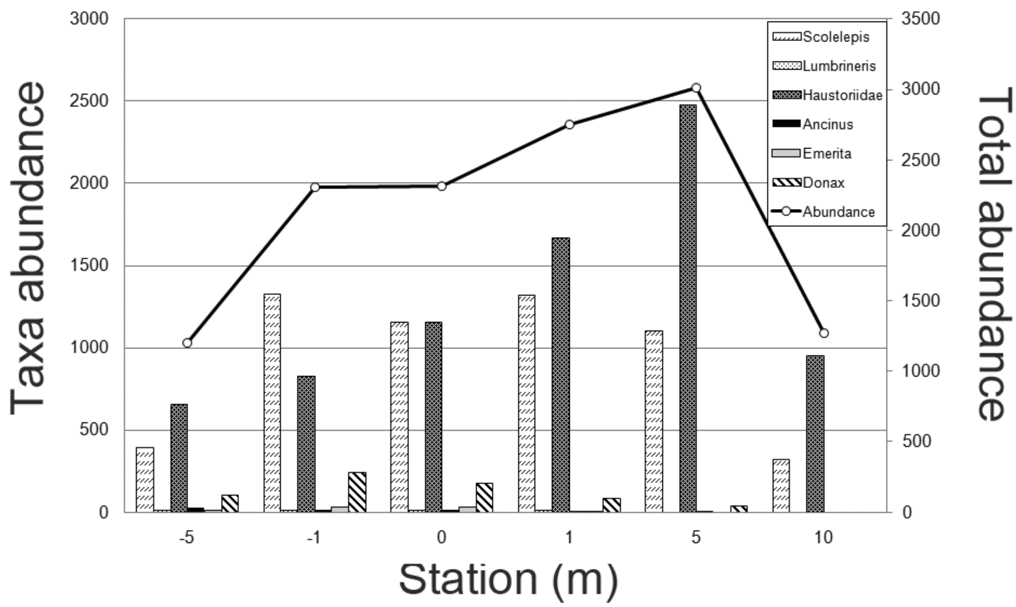

Fig. 4.7. Intertidal macrofaunal zonation across all study sites along the upper Texas coast. Y axis (bars) denotes taxa abundance counts. Secondary Y axis (line) denotes total abundance counts over all sites. Data includes counts from July 2007-August 2008.

Variation in taxa zonation was found to occur by site (Fig. 4.8). Sabine Pass and Jamaica Beach reflect the trend observed across sites with Haustoriidae occurring in greatest abundance at the 5 m station and *Scolelepis squamata* dominated the lower swash zone at the 0 m and -1m stations. High Island retained the observed trend for *S. squamata* only, as very few Haustoriidae were found at this site. Surfside Beach did not show the trend observed in the pooled abundance graph. *S. squamata* and Haustoriidae share the upper intertidal zone. Differences in the geological features at High Island and Surfside Beach were thought to the reason for the change in zonation pattern compared to Sabine Pass and Jamaica Beach. Those features identified were High Island's large grain size and small beach width and Surfside Beach's low slope and wide beach.

4.3.4 Effect of storms

Storms ravage the coastline during all seasons, which causes movement (lateral, erosional or accretion) of sediment. Arctic cold fronts ("northers") and tropical storms are common seasonally along the Texas coast. Hurricane Humberto, a category 1 hurricane, made landfall east of High Island, Texas on September 13, 2007. No negative change in physical or biological measures was measured. Statistical significance was identified in total abundance between the surveys taken before and after the hurricane. Upon examination of the data, an increase in abundance of the most common taxa at High Island (*Scolelepis squamata*) was observed but a slight decrease was observed at Sabine Pass. Richness at High Island decreased, but remained the same at Sabine Pass.

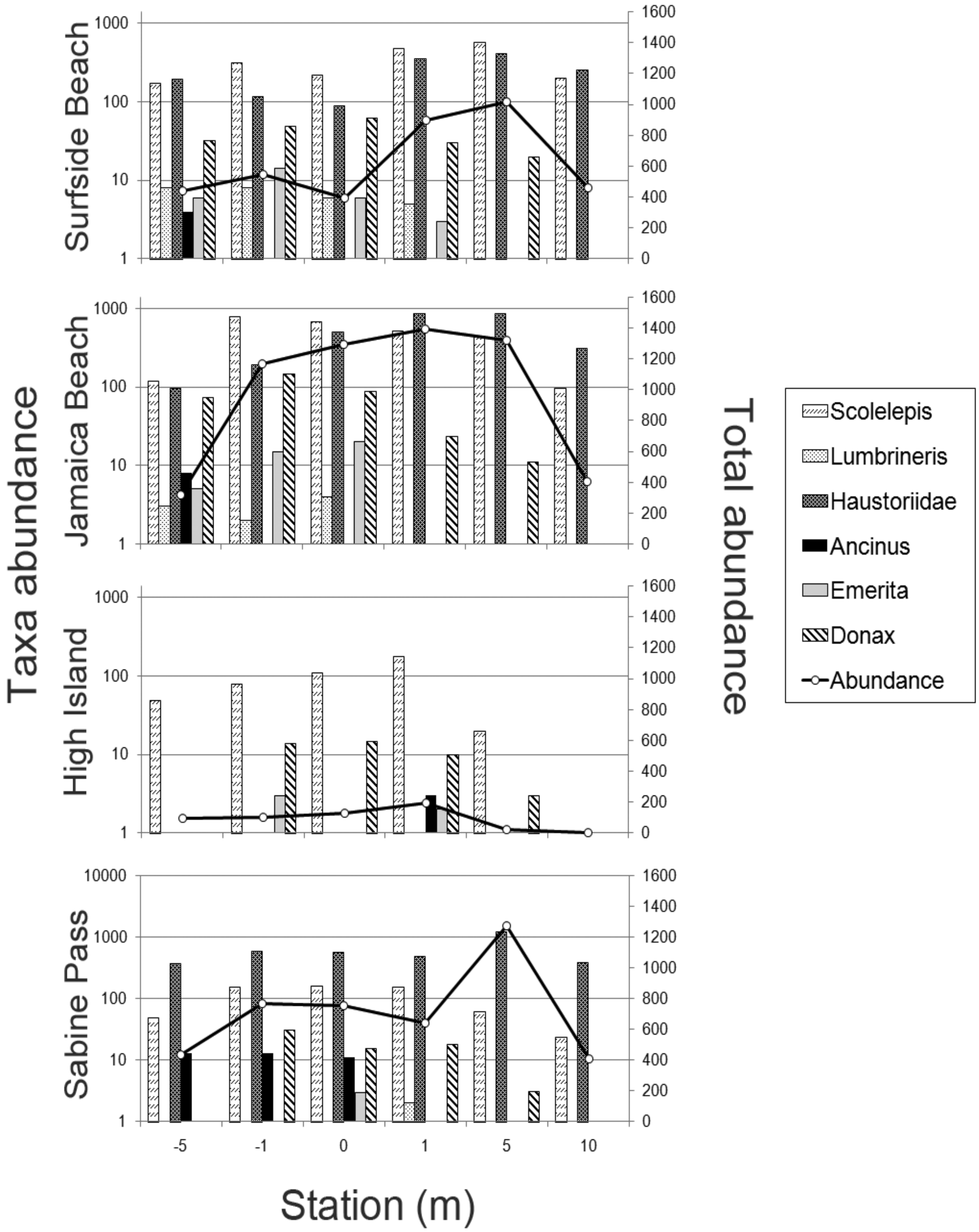

Fig. 4.8. Intertidal macrofaunal zonation with each study site along the upper Texas coast. Y axis (bars) denotes log taxa abundance counts. Secondary Y axis (line) denotes total abundance counts over all sites. Data includes counts from July 2007-August 2008.

Arctic cold fronts dip southward to the Gulf coast December through February. Although a decline in total abundance, slope, and elevation was measured from December through February, the variables were not found to be statistically significant when comparing the months of December to January nor January to February. Statistical significance across sites was identified in abundance and air temperature between the months of December to February ($p=0.018$; 0.029 respectively). Air and water temperature was found to be of statistical interest across sites between the months of December to January and water temperature across sites for January to February ($p=0.057$ for both).

4.3.5 Community analysis

To better understand community ecosystem, one site, Jamaica Beach was heavily sampled in an effort to obtain a one-time snapshot of the site, community diversity, and gage previous research thoroughness. 91 total samples were taken with 9 taxa identified from 7 station levels. Taxa richness was greater in the lower stations (analogous to swash and low intertidal zone in monthly study, stations 1, 2 and 3) than in the drier intertidal (mid-and upper intertidal, stations 6 and 7) (6-8, 1-2 taxa respectively). Abundance was greatest in the mid-to upper stations (mid-intertidal, stations 4 and 5) as found during the monthly sampling. Shannon's diversity reflected the same disparity with greater values in the swash and low intertidal (1.85-1.39) than at the mid-intertidal zone (0.67-0.18). *Scolelepis squamata* and Haustoriidae, the most abundant taxa, exhibited zonation similar to previous analysis. Zone 4 is equivalent to 3.3 m during each monthly survey. Both Haustoriidae and *S. squamata* were commonly found at this zone. Haustoriidae was next most commonly found at Zone 5, equivalent to zone 6.6 m. As the average abundance of *S. squamata* and Haustoriidae increased the standard deviation of the average abundance increased. Examination of rarefaction analysis found that asymptotic values on taxa were found to differ by zone (Fig. 4.9). It could be interpreted that stations with higher richness require more sampling (lower intertidal and swash zone). This is not dependent upon abundance. Comparing the three years of June abundances, there were statistical significant differences (p=0.034). Pairwise comparisons revealed that the more abundant 2008 June data was the cause of the statistical significance. June 2007 and 2009 samples were not statistically different.

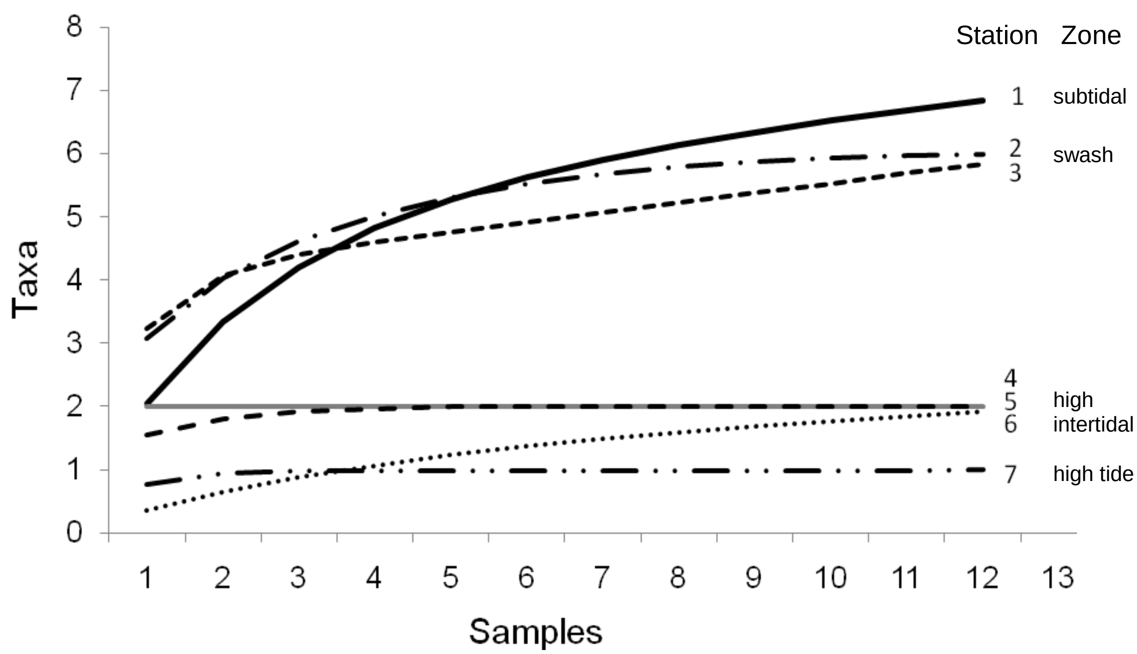

Fig. 4.9. Rarefaction analysis of Jamaica Beach community analysis. Each taxa diversity curve from stations sampled June 2009. Numbers within chart denote stations with the lower numbers located downshore, seaward.

4.4 Discussion

4.4.1 Sandy beach community

Long thought of as the desert of ocean systems, sandy beach ecosystems have a dynamic of daily and seasonal organismal migration and change. Although sandy beaches are species poor, the taxa found there survive under dynamic and harsh conditions. Attempts to define conditions that determine proliferation must be conducted systematically as described in this study over months and preferably years.

Sandy beach communities have been noted in previous studies as species poor, with the presence of only a few taxa (McLachlan et. al, 1993; McLachlan and Dorvlo, 2005; McLachlan and Brown, 2006). Low richness is common in disturbed communities (Copeland, 1970; Boesch et al., 1976; Barnett, 1981; Sousa 1984). Along the upper Texas coast the total richness during the study period was valued at 22 taxa. Monthly richness did not exceed nine taxa per sample with six taxa constituting 96% of the population. Two taxa, *Scolelepis squamata* and Haustoriidae, dominated the population constituting 92% of the population. Those two taxa are common in disturbed communities and have been found to be early colonizers in newly disturbed communities with *S. squamata* typically one of the first colonizers (Jaramillo et al., 1987). The top six abundant and common taxa are known to be mobile following the intertidal zone as it migrates up and down the beach face (Croker et al., 1975; Croker, 1977; Leber, 1982; Britton and Morton, 1989).

The study sites along the Texas coast in this study are dissipative ($\Omega > 5$). Because these sites are characterized as flat beaches, zonation can be difficult to identify.

Dahl (1952) and Salvat (1964) suggested two methods in defining zonation, by characteristic crustaceans or physical parameters. As found by further studies (McLachlan and Jaramillo, 1995; Defeo and McLachlan 2005; McLachlan and Brown, 2006) zonation along sandy beaches varies by beach characteristics. An attempt to define macrofaunal zonation within the littoral zone was undertaken in the study. Hot, dry, fine sands and vehicular traffic restrict marine organisms along the upper Texas coast to the intertidal zone with the exception of the ghost crab, *Ocypode quadrata* (adw unpublished data). Intertidal zonation was defined by physical parameters and confirmed by community structure. Both dominant taxa, haustoriid amphipods and *Scolelepis squamata*, were found in all identified zones (low intertidal, mid-low intertidal, mid-intertidal, upper intertidal) (Rodil et. al, 2006). Each taxon dominated different zones within the intertidal. This domination held true for each site with the exception of the Surfside Beach site. This site exhibited a lower slope gradient thus a larger swash zone. This also moved the water table crop line higher on the beach allowing for a larger intertidal width. Replacement of one taxon over the other by height on the beach was not recorded. This larger zone may have reduced competition. More upper intertidal stations would need to be surveyed to further develop this idea. Other taxa occurred within the swash zone. With the exception of the bean clam, *Donax* spp., other abundant taxa were restricted to the much more saturated sediment with consistent water flow (Trueman, 1971; Schultz 1973). The bean clam, *Donax* spp., was found decreasing in abundance at the mid-intertidal and absent at the upper intertidal zone.

Zonation of the abundant macrofauna may be best understood in relation to life history traits, including tolerances of desiccation at low tide.

Life history traits in each of six abundant taxa are optimized for survival on the intertidal beach. Sediment size and type along with availability of food are two key subtidal factors in determining species composition (Gray, 1974; Snelgrove and Butman 1994; Gray and Elliott 2009). Wave action, sediment water saturation and slope may also be factors in an intertidal beach environment. Higher wave action creates a more inclement environment in which to survive, but also removes smaller grain size sediment, increased water turbidity, and increased slope. Many species will prefer a specific sediment size range. In this study variation in the upper Texas coastal sediment size was relatively small because many species were found at all sites. In general the grain size was 125 µm or less with the exception of one site. High Island's grain size differed greatly from the others during the winter months and along the upper extent of the intertidal zone. Only a few taxa with low abundance were found at this study site. The larger grain size, lack of sediment, and steeper slope at High Island most likely influenced the lack of abundance and richness values obtained during this study. Higher slope values decrease the width of the intertidal beach. Low water saturation levels found near and above the high tide negatively influenced the motility of organisms between the sediment grains.

Two feeding guilds were identified from the taxa described above. The feeding guilds were also identified by region of zonation. Filter feeders such as *Donax* and *E. portoricensis* best feed in the swash zone where particles swept in by waves can be picked out as they move closely over the sand grains (Efford, 1966; Britton and Morton, 1989; Jaramillo and Lastra, 2001). The two dominant taxa either filter and/or deposit feed, or are episammic, eating particles off of or between sand grains (Croker, 1967; Robertson and Shelton, 1967; Sameoto, 1969; Holland and Polgar, 1976; Fauchald and Jumars, 1979; Dauer, 1983; Fauchald 1983; McHugh and Fong, 2002). The ability to feed using a variety of methods allowed for their presence in multiple zonal regions.

Five of the most common species were also found nearshore, which could allow for better recruitment onto the intertidal beach (Keith and Hulings, 1965; adw unpublished). Two of the five taxa, Haustoriidae and *Ancinus depressus*, brood young which may allow for easier proliferation of those taxa in a local area (Pechenik, 1999). *S. squamata* and *Lumbrineris* sp. proliferation may also been assisted by their benthic larvae (Fauchald, 1983). The last two taxa common to beaches, *Donax* spp. and *Emerita portoricensis* have pelagic larvae where only juvenile *Donax* was found subtidally. The presence of the two dominant taxa both in the intertidal and subtidal zones along with their ability to retain young within their general area furthers their potential to dominate niches that may be adverse for other taxa. The flexibility of these generalists has allowed them to occupy the mid-intertidal and upper intertidal niche that otherwise are out of reach of many marine organisms. Sandy beaches have a higher proportion of non-dispersing larvae compared to other marine habitats (Grantham et. al., 2003).

4.4.2 Effect of seasons and climatic events on macrofauna

In this study area, as in many temperate climates, population growth during summer months is followed by a decline in winter. Analysis defined the seasons as summer (June, July, August), winter (January, February), and intermediate (April, October), because they consistently clustered the tightest when rotating the axes (Fig 4.5). Other months such as November and December were noted to cluster with the winter season and March, May and September were noted to cluster with the summer season, but they did not cluster tightly when the axes was rotated. The intermediate season identified in multivariate analysis is possibly because of similarities in community structure exist. Because of annual variability more data would need to be acquired to confirm this occurrence.

A comparison of *Scolelepis squamata* and Haustoriidae identified an initial time lag in spring population of the polychaetes. *S. squamata* peaked after the haustoriids and continued to persist in the fall with an extended decline (Fig 4.6). Defeo and McLachlan (2005) stated that in disturbance dominated environments, sandy beach fauna tended to be influenced by physical factors, instead of biologically controlled ones. Distinct competition did not seem to exist between the two taxa as similar abundance numbers was observed in the raw data. In regards to zonation, haustoriid amphipods were most dominant at the 5 m station. Haustoriids could be found at lower stations in high numbers along with *S. squamata*, but *S. squamata* was generally absent at the higher zonal stations. Because of the relative consistency of abundance number found between samples along the same zone in preferred zones, it is proposed that the patchiness in preferred zones is not high. The co-occurrence of these two species may be more physically defined such as grain size, food availability, temperature (Gray, 1974; Snelgrove and Butman, 1994; Defeo and McLachlan, 2005; Rodil et al., 2006). *Emerita* found only in the swash during the summer months as was to be expected because of its life history trait, i.e. pelagic larvae.

The initial summer population abundance counts were lower than observed during the second summer sampling. Community structure was similar in that a multivariate analysis that concluded the high similarity between the two year's data. The differences in counts could be caused by the larger amount of *Sargassum*, gulf seaweed, deposited upon the beach during the first summer. A deposition depth of greater than 0.5 m of seaweed was observed during the month of July, with continued deposits observed through September 2007. During the second year the amount of gulf weed did not cover the intertidal zone as previously observed. Large amounts of *Sargassum* starve the sediments of oxygen creating an anoxic layer in which beach organisms could not survive.

Along the upper Texas coast two specific types of storms are noted for causing changes in the environment (Hayes, 1967; Morton et. al, 1994; Gibeaut et. al, 2002; Morton and Sallenger, 2003; Stone, et al., 2004). Small hurricanes and tropical storms, that did not cause identifiable changes in the physical environment such as temperature, slope, elevation, or sediment grain size, did not affect the intertidal community during this 15 month study. Storms that caused change during this study were "northers" which brought a drop and continued lower temperatures. The fall in air and sea temperatures resulted in a decline in community abundance. Other factors associated with winter months were change in sediment grain size, elevation and slope change, but temperature was only of significant interest.

4.4.3 Conclusion

Multi-year studies are necessary for understanding community structure and assemblages. This 15 month study demonstrated the variability in annual abundance counts and the necessity to collect of over a longer period of time. Although abundance counts differed annually, the community structure was relevantly similar as observed in the multivariate analyses. Species richness along the upper Texas coast was relatively low with higher richness observed in the lowest zones also observed by McLachlan (1990).

Macroinfaunal zonation was identified within the intertidal zone. The two dominant taxa were present in all zones but abundance counts were higher in their respectively preferred zone. Other taxa common to the intertidal zone were restricted to the saturated sands of the swash and lowest intertidal. Life history traits dictate the zonal possibilities. Mobility and adaptability appear to be the key to survival on the intertidal beach. Leber (1982) noted the presence of macrofauna overlapping both intertidal and subtidal as observed during this study. He also noted that macrofaunal zonation was not as discretely identified as physical zones. Zonation was noted to vary between sites because of beach geomorphology. Wider beaches and an increased intertidal zone decreased the distinct abundance zonation found in the two dominant taxa. Reduced competition for the preferred wet zone just outside the swash best explained this observable trend.

This often overlooked ecosystem is both of economic and ecological importance. Although increased tourism and infrastructure development endangers the natural coastline, the increased interest in beach management may assist in its continued existence. Loss of sediment and natural shoreline retreat will negatively affect the organisms. Ecologically, *Donax*, amphipods, and other small crustaceans living in the sediment are an important food source for birds and juvenile fish (Leber, 1982; Peterson et al., 2006). As the upper Texas coast is along the Central Flyway, a major bird migratory path, the loss of this ecosystem would a put strain on other nearby food sources. Further long term studies to understand the variability and resilience of this ecosystem is a necessity in beach conservation and management.

Species list of intertidal macrofauna identified may be found in Appendix C. Supplemental and raw data on beach intertidal macrofauna may be found in Appendix D.

CHAPTER V

IMMEDIATE EFFECTS OF HURRICANE IKE ON BEACHES OF THE UPPER TEXAS COAST

5.1 Introduction

Hurricanes are short-term (pulse) events known for destructive effects on ecosystems (Davis et al., 2004; Morton and Sallenger, 2003; Stone et al., 2004; Defeo and McLachlan, 2005). This type of intense disturbance affecting sandy beaches had been observed to cause immediate change in community assemblages (Croker, 1968; Dobbs and Vozarik, 1983). Differences in abundance and richness counts after a strong storm can vary upon the strength, duration, and/or location of storm landfall (Boesch et al., 1976; Yeo and Risk, 1979; Posey et al., 1996; Dreyer et al., 2005; Gardner et al., 2005). Some storms or disturbances cause a habitat alteration which may affect organismal diversity until a return to previous state or balance is achieved, taking months to years (Grassle and Grassle, 1974; Dobbs and Vozarik, 1983; Jaramillo et al., 1987; Dreyer et al., 2005). Significant changes have also been noted in salinity, oxygen depletion, and sedimentation (Keith and Hulings, 1965; Boesch, et al. 1976; Davis et al. 2004). The brunt of hurricane winds and surge is felt initially on the open coastline or beach face. The reworking of sediments from storm impacts can affect the coastline for many years (Morton and Paine, 1985; Jaramillo et al., 1987; Morton et al., 1994).

Storm impacts can be severe on the upper Texas coastal beaches. Storm surge can be especially damaging to a microtidal environment such as the upper Texas coast where tides are typically less than 1m with a diurnal/semidiurnal tidal cycle dependent upon moon phase (quarter moon phase = mixed semidiurnal). Wave height is typically less than 1 m with grain size previously estimated between 125-63 µm (Bullard, 1942; pers. obvs.). High energy storm waves can easily remove the smaller sized sediments to nearshore bars changing the habitat for intertidal macrofauna (Keith and Hulings, 1965; Hayes, 1967; Morton and Paine, 1985; Watson, 1999).

The upper Texas coast is highly developed and populated, supporting a population of greater than 5.5 million (Anderson, 2007; U.S. Census, 2008). The heavy development and population add to the existing coastal erosion through the loss of dune fields and the addition of hard structures such as seawalls, groins, jetties, and river modification through dams and flood control (Mathewson and Minter, 1981). Also adding to the erosional loss on Texas beaches is the permissible vehicular traffic (Anders and Leatherman, 1987). Throughout the latter half of the 20^{th} century the Texas coastline has been experiencing increased erosion, especially along the barrier islands and headlands (Morton et al., 2005). Some areas along the upper Texas coast experience losses of more than 2.5 m per year on average (Coastal Studies Group, BEG, 2009). This instability combined with sea level rise and the arrival of seasonal tropical storms creates a highly dynamic physical environment in which intertidal beach organisms must struggle for survival against changing habitat structure. The community richness along this portion of the Texas coast is typically low as in any disturbed area, high stress environment or habitats with low heterogeneity (McLachlan, 1983; Sousa, 1984; Tews et al., 2004; Speybroeck et al., 2006).

On September 1, 2008 Tropical Storm Ike formed off Cape Verde (Berg, 2010). Peaking at a category 4 rating with 233 km/hr winds, Hurricane Ike had the largest diameter ever recorded in the Atlantic basin with storm winds extending 445 km from the center (NCDC, 2008). On September 13 Hurricane Ike made landfall on Galveston Island, Texas, USA as a category 2 storm with winds of 177 km/ph (2008 Saffir-Simpson scaling) (Berg, 2010). The accompanying surge was higher than its category rating with maximum observed surge at 5.33 m (Berg, 2010). Surveys of the upper Texas coast were conducted the month before and just after the hurricane to measure seasonal and storm event changes on the benthic intertidal macrofauna. Measurements included elevation, slope, sediment grain size, beach face width, and intertidal community ecology. To examine the effects of Hurricane Ike, macrofaunal communities were compared before and after the storm on four sandy beaches on the upper Texas coast.

5.2 Materials and methods

As part of a Ph.D. project four sites had been selected on open coast beaches from the Texas-Louisiana border to the Freeport area prior to the hurricane (Fig. 5.1). Sites were selected approximately 30-60 km apart to increase site variability (i.e. elevation, dune presence, grain size, and human impact) and probability of storm disturbance. Sites were named by the nearest municipality.

A beach elevation survey was conducted before and after the storm at each site along a transect line with an established benchmark. Physical benchmarks were identified and set at each location fixed by GPS. Surveys ran from the benchmark to the shoreline including 5 m into the intertidal zone. Elevation was normalized to the North American Vertical Datum 1988 (NAVD ’88) using the mean low low water mark (MLLW) verified data from NOS station, Galveston Pleasure Pier, TX Station ID: 8771510 for Jamaica Beach, High Island, and Sabine Pass site and NOS station, USCG Freeport, TX Station ID: 8772447 for Surfside Beach. Elevation and beach width were measured using the physical benchmark as a common point of reference on the first transect alone. A second transect was set up in the intertidal zone 10 m from the survey line marking locations for core samples. Cylindrical cores measuring 10 cm diameter by 10 cm long were taken at specified shore normal intervals (10 m, 5 m, 1 m, 0, -1 m, -5 m stations; negative numbers are seaward) to measure macrofaunal community structure along each transect. Core intervals were measured from relative sea level (“0”) at the time sampled. Relative sea level was determined by the average of the highest wave run-up. A total of 12 cores were taken at each beach every month, 6 along each transect. Cores were sieved through a 1 mm mesh bucket. Materials retained on the sieve, fauna and shell remnants, were preserved in 10% buffered formalin and taken to Texas A&M University, College Station, Texas for sorting and identification. Faunal identification was carried out to the lowest possible taxonomic level.

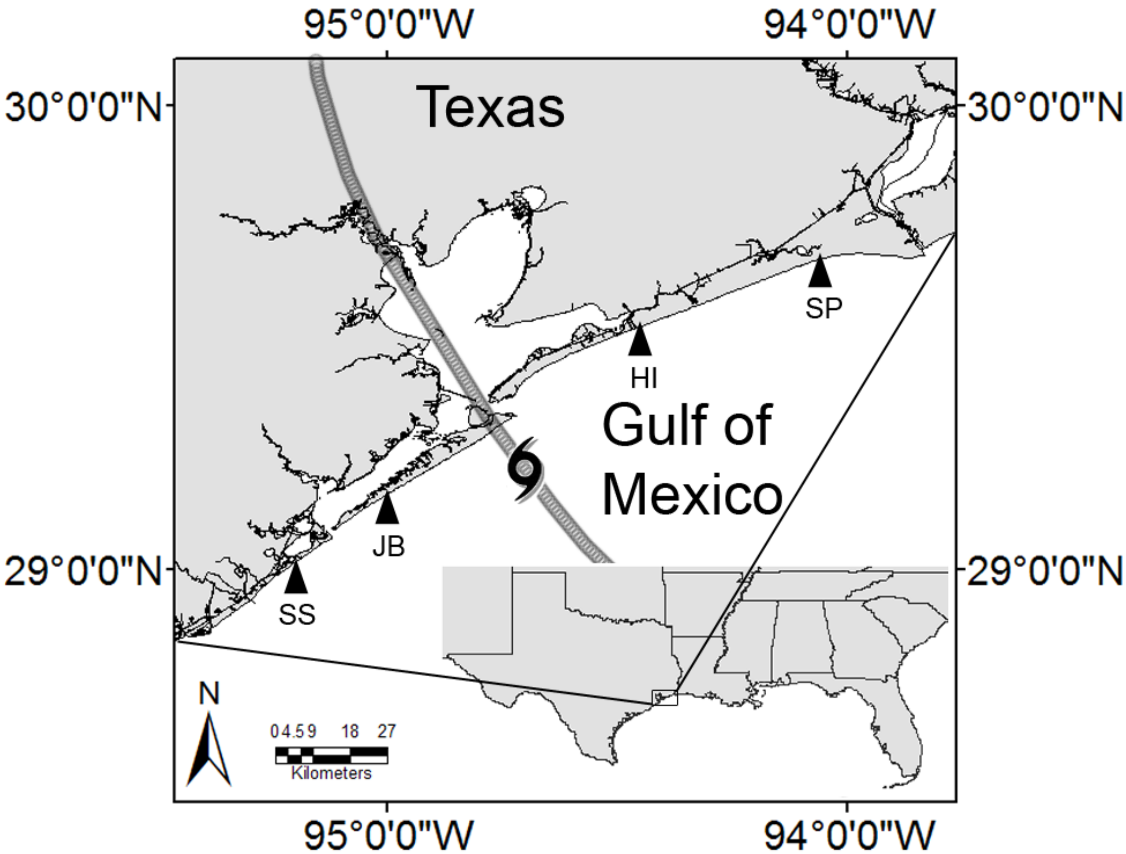

Fig. 5.1. Map of upper Texas coast. Four study sites named by nearest municipality, Sabine Pass (SP), High Island (HI), Jamaica Beach (JB), Surfside Beach (SS). Line in middle indicates the path of Hurricane Ike through the upper Texas coast.

One sediment core was collected at the relative sea level each month per site to examine sediment grain size. Sediment was dried for several days at 35° C until a constant weight was achieved and then sorted using a RO-TAP Testing Sieve Shaker into 6 size classes ranging from 2 - 0.063 mm: pebble (2 mm), coarse sand (600 µm), medium sand (250 µm), fine sand (125 µm), very fine sand (63 µm), and silt/clay (< 63 µm). Sediment grain size was determined by the mode.

Study sites were sampled August 16-17, 2008, three weeks before the Hurricane Ike struck the Texas coast. After Hurricane Ike, collections were taken September 20, 2008, (Sabine Pass and Surfside Beach) and September 27, 2008 (Jamaica Beach and High Island), one and two weeks after the storm. The delayed sampling conducted in September at Jamaica Beach and High Island was because of restricted access to sites.

To aid in the interpretation of macrofaunal differences before and after Hurricane Ike, abundance and richness for each beach was determined by pooling the six cores from each transect for mean and standard deviation (0.048 m^2). Zonation means were calculated by transect and station level. Taxa were pooled across all sites for total abundance (0.38 m^2). Although reflecting similar hurricane effect trends, High Island was excluded in the computation in the “All Sites” value of means and in zonation. The High Island site is very atypical for upper Texas coast beaches, subject to intense sediment scouring during much of the year consequentially comprising of severely depressed macrofaunal populations. Comparison of intertidal macrofaunal differences before and after Hurricane Ike was made using ANOVA (α=0.05) by transect and site. When the normality test was not significant, the Kruskal-Wallis test was used for comparisons at the same significance level. Analyses were conducted in SPSS, version 16.0.

5.3 Results

5.3.1 Physical effects

Physical measurements indicated major changes in the beach habitat, including grain size, slope, and beach width (Table 5.1). Grain size increased at least one full Wentworth size class after the hurricane (p=0.04 across all sites). The beach face slope recorded at each site decreased from August 2008 (pre-Ike) to September 2008 (post-Ike), flattening the beach, (p=0.04 across all sites). Comparison of beach profiles also demonstrated the flattening of the study beaches by Hurricane Ike. The amount of vertical sediment loss on the beach averaged 0.5 m across the beach, except for Surfside Beach. At Surfside Beach sediment deposition (increase of 0.5m) was observed in the lower intertidal. Some areas along the beach, i.e. beach dunes, lost an addition 1-2 m vertical height (Fig. 5.2). This was observed in the change of both the elevation measurement and the migration of the observed high tide**,** which migrated landward (distance varied from 5-38 m). Measured beach face widths from the established GPS benchmarks decreased at every location except for one (Surfside Beach) where it increased slightly (p=0.45 across all sites). The decrease in beach face width as measured from the original “dune line”, stationary GPS benchmark to the water line, also supported the evidence of sediment loss; some variation in this measure was dependent upon the timing of the surveys in relation to tide. The Surfside Beach study site experienced sediment accretion at the intertidal zone and greater flattening of the beach face (Fig. 5.2). Observations made after the hurricane included noticeable sandbars increasing from zero in August to three in September at all beaches, flattening of upper beach dunes (loss of 2.38 m at Jamaica Beach), and decreasing washover patterns north to south (Fig. 5.3). Washover pattern lessened as distance from hurricane landfall increased as well as in areas located southwest of landfall. The northeastern landfall side experienced stronger wind and wave effects.

Table 5.1. Geological measurements from study sites along upper Texas coast. Measurements taken before (August 2008) and after (September 2008) Hurricane Ike landfall. Slope and beach width was measured from benchmark to relative sea level. Migration is the landward movement of the high tide line from the mean summer position to September, after the storm.

Site	Grain size August (µm)	Grain size September (µm)	Beach slope August (°)	Beach slope September (°)	Beach width summer 2008 mean±sd (m)	Beach width September (m)	High tide migration (m)
Sabine Pass	125	660	1.82	1.46	43±9	30	12.2
High Island	125	shale	3.04	1.18	29±9	17	26.7
Jamaica Beach	63	125	2.45	1.63	38±7	0	38.2
Surfside Beach	63	125	1.63	0.93	50±13	66	5.5

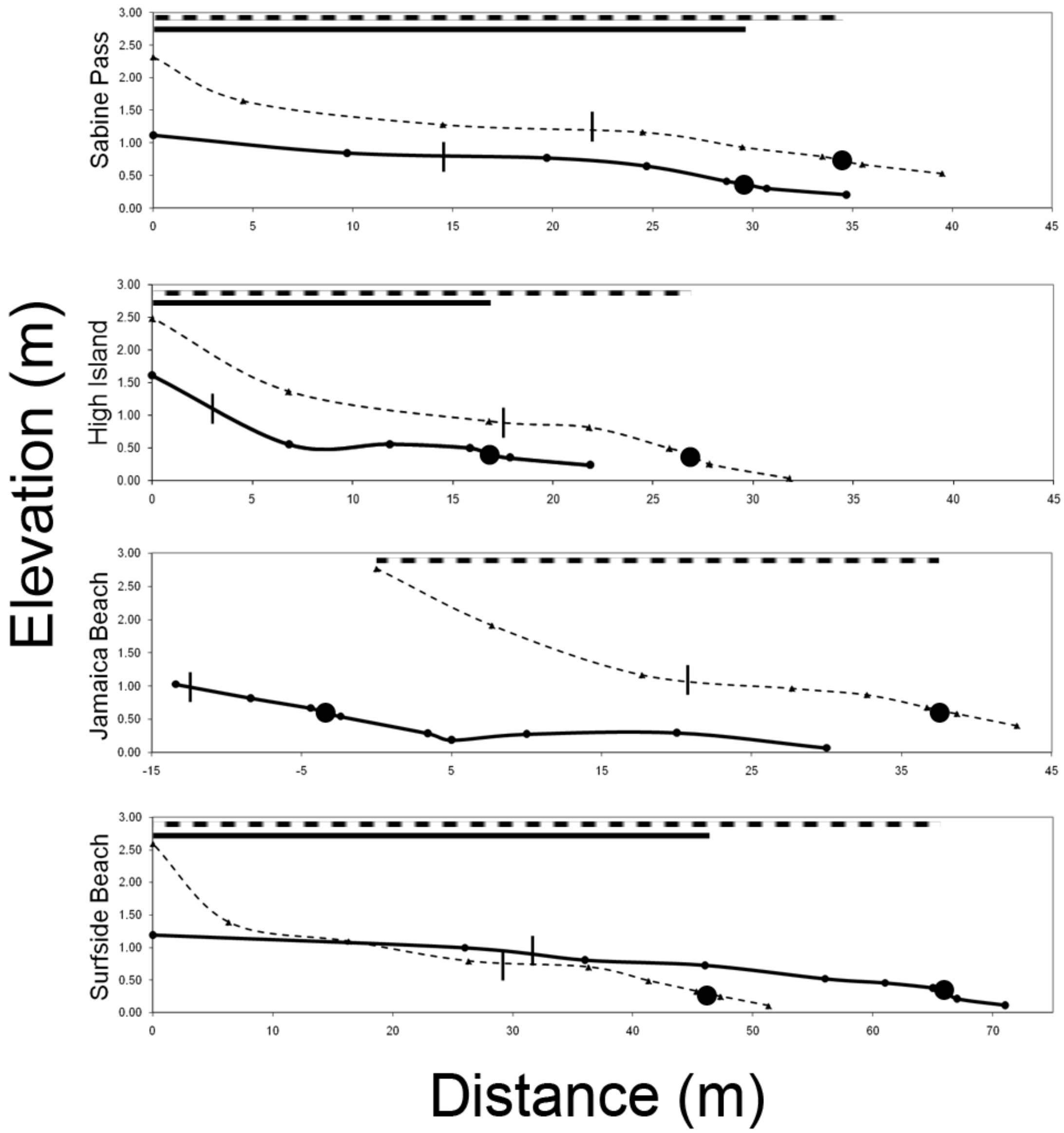

Fig. 5.2. Elevation profiles of each of the four upper Texas beach survey sites. Dashed line illustrates August 2008 (pre-Ike) elevation. Thick black line illustrates September 2008 (post-Ike) elevation. Line was smoothed between points. Large dot along the line indicates relative sea level at the time of survey. Recent high tide is marked by a cross hatch. “0” along the horizontal axis designates GPS benchmark. Dashed line at top of each graph measures August (pre-Ike) beach width from GPS benchmark to relative sea level; solid line at top measures September (post-Ike) beach width. Jamaica Beach benchmark in September was under water, no beach width measured.

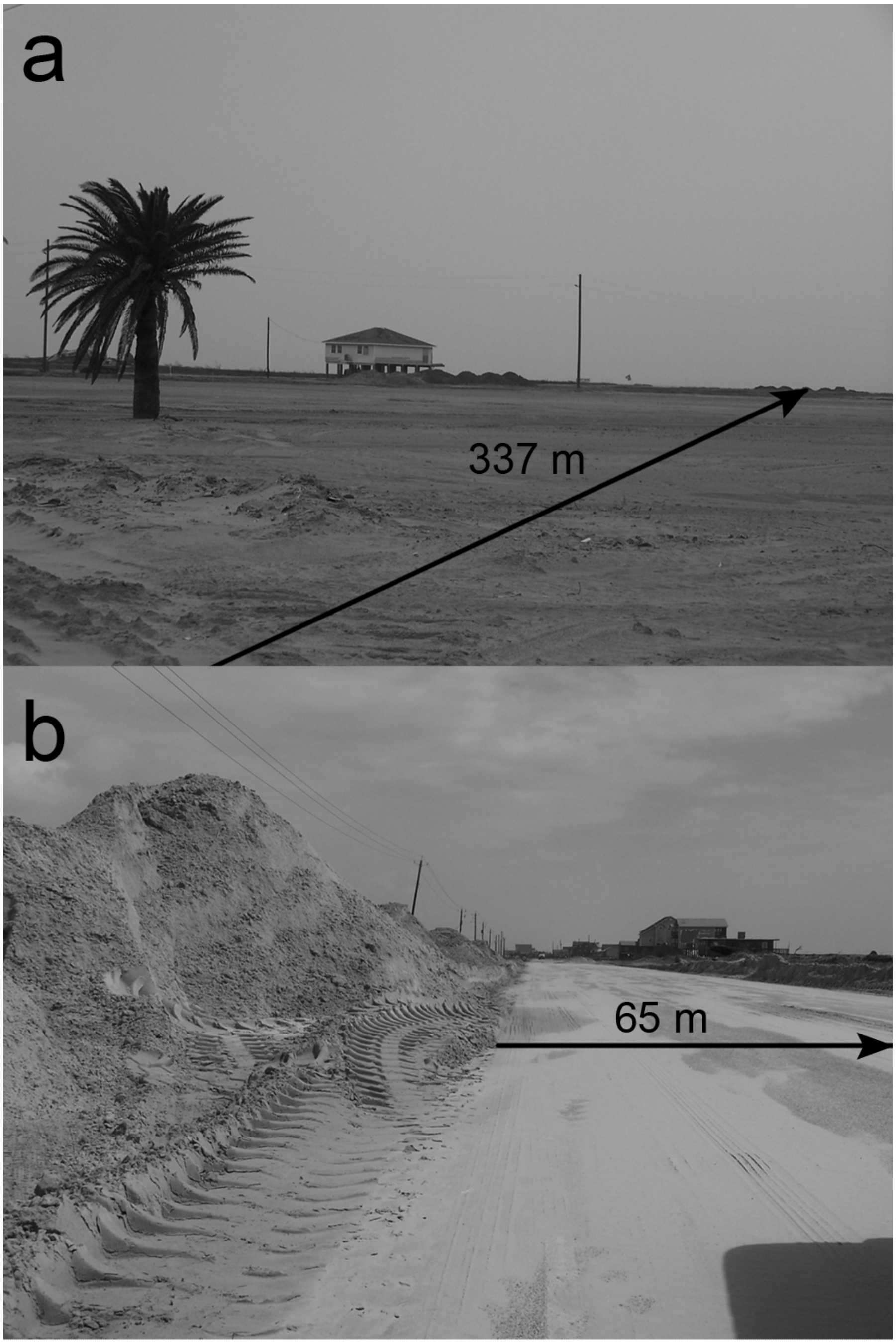

Fig. 5.3. Examples of hurricane washover deposits (a) and removal of the deposits (b). Arrows point to shoreline. (a) Foredunes location before the storm to the end of the hurricane washover fan was 337 m at this Bolivar Peninsula site near Caplan, Texas. Picture was taken along State Highway 87. (b) Foredunes location before the storm to the end of the washover fan was 65 m at this site on Follets Island near Surfside Beach, Texas. Picture taken along County Road 257. Large sand piled, left side, indicates washover deposits removed from road.

5.3.2 Biological effects

Overall a 33% reduction in species richness was observed between samples taken before and after the storm. Twenty-two intertidal benthic macrofaunal taxa were identified along the upper Texas coast before the hurricane in previous surveys. Six of those taxa were found commonly (Haustoriidae, *Scolelepis squamata*¸ *Lumbrineris* sp., *Donax* sp., *Emerita portoricensis,* and *Ancinus depressus*) (Table 5.2). After the hurricane only six benthic intertidal macrofaunal taxa were recorded (Haustoriidae, *Scolelepis squamata*¸ *Lumbrineris* sp., *Donax* spp., *Emerita portoricensis*, and *Callichirus islagrande*). The two most common and abundant macrofauna, the polychaete worm *Scolelepis squamata* and the amphipod family Haustoriidae, were the only two intertidal macrofauna with appreciable numbers after the hurricane (Table 5.2).

Table 5.2. Intertidal macrofauna abundance pooled across study sites along the upper Texas coast. Measurements taken before (August 2008) and after (September 2008) Hurricane Ike landfall. * denotes statistically significant results.

Species	August	September	p-value
Haustoriidae	709	216	0.15
Scolelepis squamata	1709	87	0.002*
Lumbrineris sp.	13	5	0.48
Donax spp.	290	29	0.05*
Emerita portoricensis	47	1	0.03*
Ancinus depressus	3	0	0.06
Callichirus islagrande	0	1	0.33
Total	2771	339	0.005*

After the hurricane less than 13% of the sampled intertidal macrofauna were present compared to the pre-hurricane total beach abundance count recorded in August 2008. Faunal abundance differed significantly between sampling dates, declining from 2,771/0.38 m^2 (August 2008) to 339/0.38 m^2 (September 2008) ($p=0.005$) (Table 5.2). The mean transect abundance of macrofauna for all sites exhibited a similar 88% loss along with richness ($p=<0.001$, 0.001, respectively) (Table 5.3; Fig. 5.4). Statistically significant differences in pooled abundance were found for each of the common species except for Haustoriidae and *Lumbrineris* sp.

Table 5.3. Intertidal macrofaunal mean transect abundance (n) and richness (s) counts including standard deviation (sd) from study sites along the upper Texas coast. Measurements taken before (August 2008) and after (September 2008) Hurricane Ike landfall. Only one measurement was taken at Sabine Pass, no p-value available. P-values calculated by one way ANOVA. “All Sites” does not include High Island values. * denotes statistically significant results.

Site	August macrofaunal mean n±sd	September macrofaunal mean n±sd	August macrofaunal mean s±sd	September macrofaunal mean s±sd	n p-value	s p-value
Sabine Pass	522	15	5	4	n/a	n/a
High Island	58±11	0	1.5±0.7	0±0	0.02*	0.10
Jamaica Beach	477±49	114±43	5.5±0.7	3±0	0.02*	0.04*
Surfside Beach	591±32	48±3	5.5±0.7	4±0	0.002*	0.10
All Sites	531±64	68±49	5.4±0.6	3.8±0.6	<0.001*	0.001*

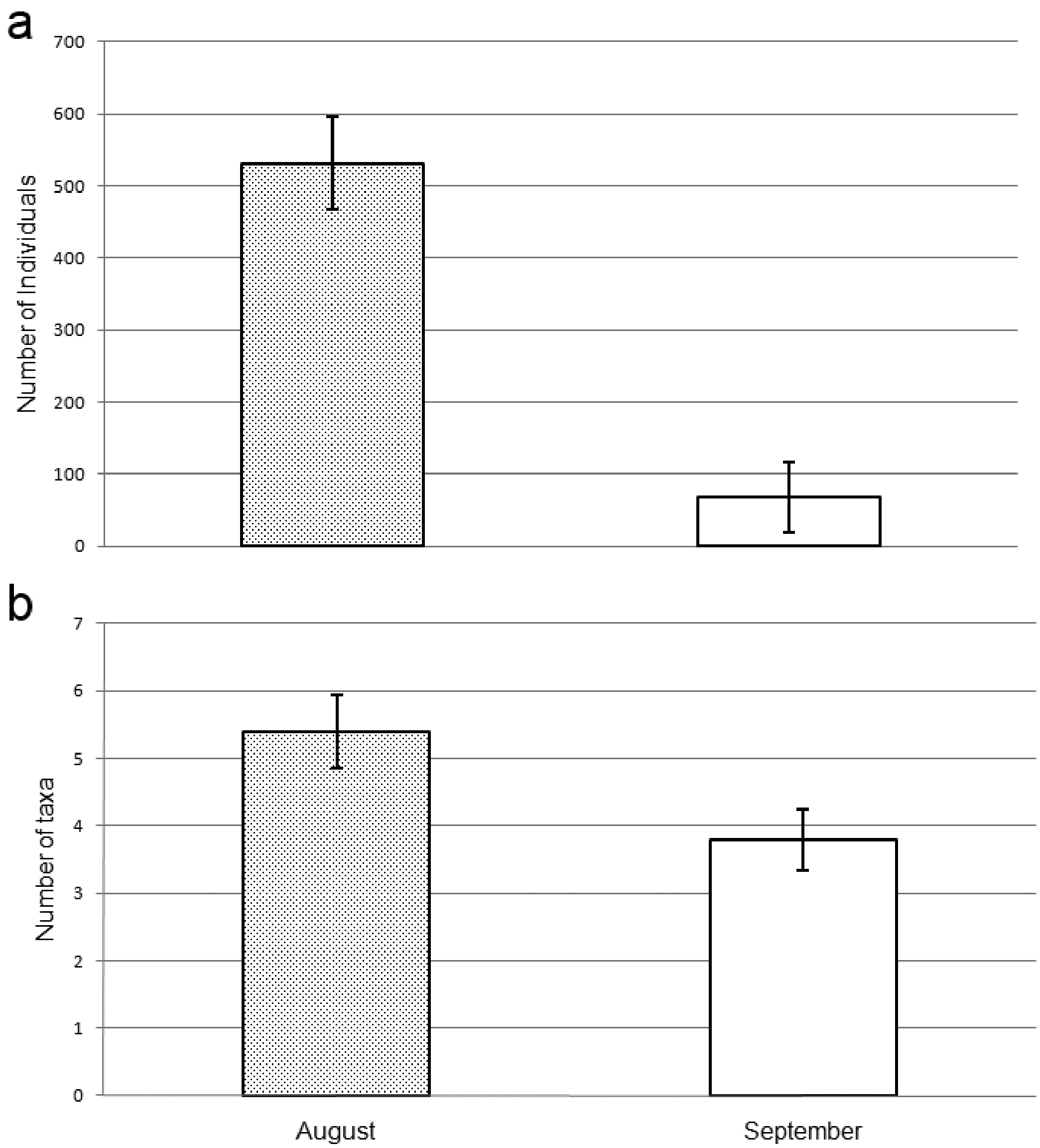

Fig. 5.4. Before (August) and after (September) Hurricane Ike mean abundance (a) and richness (b) values with respective standard deviations. Mean abundance was determined by transect across all sites, does not include values from High Island.

Intertidal macrofaunal abundance was affected by season with counts greatest in summer and early fall (June-September). The lowest abundance counts were found during the months of January and February (winter). The total abundance counts found during September 2008 (post hurricane Ike) were similar to values observed during the previous 2007-2008 winter season (p=0.22) but more depressed (Table 5.4). Comparison of September abundance to summer counts showed differences that were statistically significant (p=<0.001). Richness of infauna in September followed the same trend as abundance for winter and summer comparisons (p=0.553, 0.009 respectively).

Table 5.4. Seasonal macrofaunal mean transect abundance (n) including standard deviation (sd) from study sites along the upper Texas coast. Winter 2008, averaged January-February and summer 2008, averaged June-August, values for mean abundance of macrofauna per transect prior to the hurricane. P-values determined by Kruskal-Wallis tests. "All Sites" does not include High Island values. * denotes statistically significant results.

Site	Winter 2008 mean n±sd	Summer 2008 mean n±sd	Winter 2008 mean s±sd	Summer 2008 mean s±sd	n p-value	s p-value
Sabine Pass	26±24	478±162	2±1.7	4.2±1.3	0.05*	0.13
High Island	31±9	52±11	1±0	2.7±1.8	0.03*	0.02*
Jamaica Beach	196±83	797±291	3.7±0.6	4.7±0.8	0.01*	0.04*
Surfside Beach	78±41	678±139	3±1	5.8±0.8	0.01*	0.02*
All Sites	74±89	661±238	2.4±1.4	4.9±1.1	<0.001*	0.001*

During the study zonation was identified based upon physical parameters. The -5 m station, low intertidal zone, was just below the swash and underwater. Swash overran the -1 m 0 m, and 1 m stations. The 5 m station, mid-intertidal zone, was just above the swash zone comprising of wet sand. The highest station, 10 m above relative sea level, was relatively dry or damp sand, upper intertidal zone. Zonation patterns of the two most common macrofaunal taxa, Haustoriidae and *Scolelepis squamata*, did not differ statistically before and after the storm (p=0.40, 0.64 respectively). A noticeable pattern may be observed in Haustoriidae before the storm as they were most commonly found at the mid-intertidal zone, 5 m (Fig. 5.5). *Scolelepis squamata* appeared more common along the middle zonal stations (-1 m, 0 m, 1 m) peaking at the 5 m station. Organisms drastically declined in the upper most station/zone. After the hurricane zonation patterns were no longer apparent. The flattening of the beach was not observed to result in a wider dispersal of macroinfauna as the upper most stations remained low in abundance both before and after the storm.

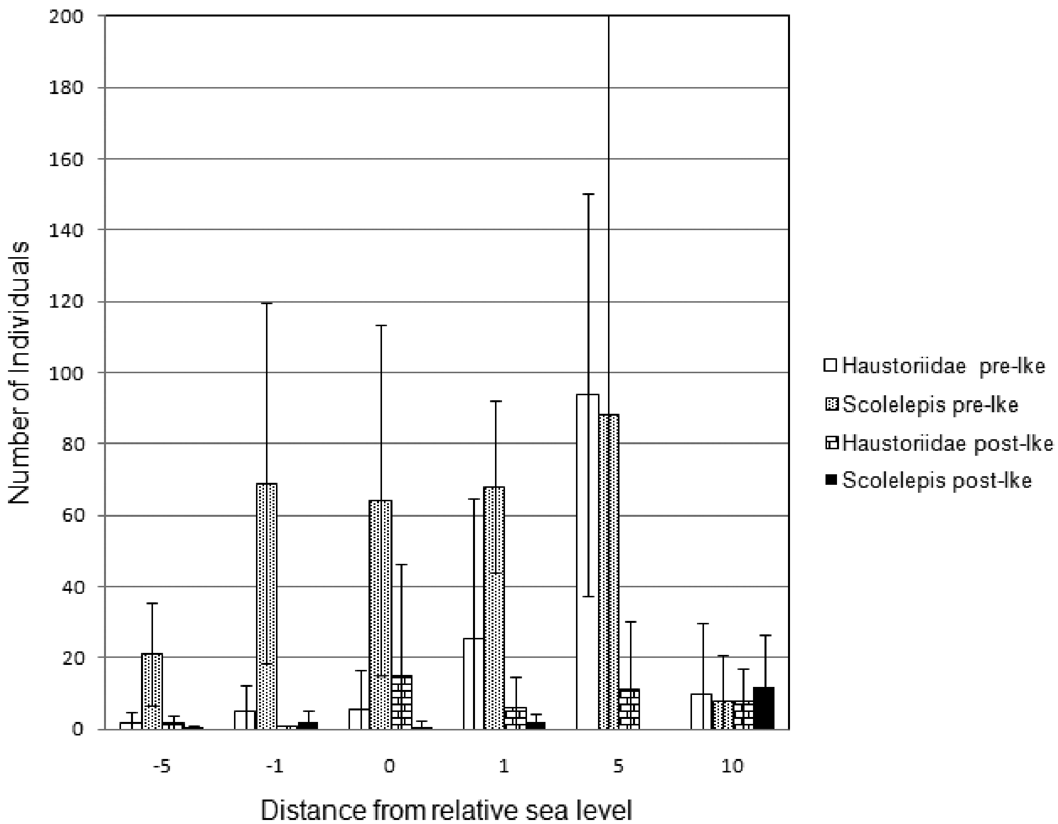

Fig. 5.5. Zonation patterns of the two most common taxa, Haustoriidae and *Scolelepis squamata*. Depicts pre-Ike (August) and post-Ike (September) mean abundance values along with respective standard deviations. Zones (interval stations) were relative to sea level at the time sampled. Mean abundance calculated by station level and transect across all sites, does not include values from High Island.

5.4 Discussion

Beach ecosystems exhibited significant and immediate physical and ecological changes in response to the pulse disturbance associated with a major hurricane (Morton and Sallenger, 2003; Davis et al., 2004; Stone et al., 2004). These changes included alteration in intertidal habitat quantity and quality and reduced species richness and abundance of intertidal macroinfauna.

5.4.1 Physical effects

Physical measurements showed that the sediment and beach profile were directly altered by the high waves and surge that accompanied the hurricane. Storm events can make a normally accretionary summer beach look like a normally erosional winter beach as strong waves remove lighter sediment to nearshore sand bars and produce a steeper beach face. In contrast, hurricanes can remove a greater amount of sediment, flattening a beach with deposition occurring both on the land and in nearshore and/or offshore sand bars (Kumar and Sanders, 1976; Morton et al., 1994). Changes in beach elevation, sediment grain size and slope were caused by movement of beach sediment further on land through hurricane washover fans and to offshore sandbars (Smith and Jackson, 1992; Watson, 1999; Woodroffe, 2002). East Texas deposits along the coastline are very thin (Rodriguez et al., 2001). This can be extremely damaging to an ecosystem if all sediments are removed as observed at High Island. Much of the sediment along the coastline was moved through wave action and surge beyond the dunes creating large washover fans (Fig. 5.3). These landward-shifted sediments were lost to the beach ecosystem and can only return through human intervention (Fig. 5.3b). Beach sediment was also lost to nearshore sandbars as the storm stirred up sediments and suspended them in the water column (Rodolfo et al., 1971; Reineck and Singh, 1972; Watson, 1999). Sediment removed from upper beach face and dunes has been noted to be deposited in offshore sandbars and within the intertidal zone (Bird, 2008). Fine sediments consisting of silt and clays may be carried a greater distance offshore than sediments of larger particle sizes. Depending upon storm intensity fine sediments may deposit a great distance offshore not to be returned to the beach (Watson, 1999). Hurricane Ike flattened the beaches creating large nearshore sandbars that were not present the month before. The amount of vertical sediment loss on the beach averaged 0.5 m across the beach except for Surfside Beach. At Surfside Beach sediment deposition (increase of 0.5 m) was observed in the lower intertidal. This site was the furthest from the hurricane landfall, on the “weaker”, western side of the hurricane, and downdrift of longshore transport. It is possible that accretion may be from other beaches.

5.4.2 Biological effects

Benthic macroinvertebrates were directly affected by changes in the geological environment. Both organismal abundance and richness within the intertidal zone decreased greatly after the hurricane (Table 5.3). There are several possible explanations for this decrease in abundance and richness. The community structure change was most likely attributed to habitat destruction, loss and accretion of sediment in the top layer (Kumar and Sanders, 1976; Dobbs and Vozarik, 1983). Loss of sediment on the beach could equate to the loss of animals as the sediment was taken onshore or deposited in nearshore sandbar (Kumar and Sanders, 1976; McLachlan, 1977). The movement of sand could have also bury many of the organisms to a depth where they are unable to recover (Posey et al., 1996; Watson, 1999). In addition to extensive sediment movement after the storm, each beach experienced an increase in sediment grain size. Survey beaches were sampled the month prior to landfall of Hurricane Ike. Beaches with finer sediments (125-63 μm) had greater biological richness and abundance than those with coarser sediments (Tables 5.1, 5.3). Post-hurricane Ike, beach grain size increased at all four survey beaches. Many benthic organisms prefer a specific sediment type (Gray, 1974; Snelgrove and Butman, 1994). Change in sediment grain size has been noted to change the composition of the species present (McLachlan, 1977; Dobbs and Vozarik, 1983; McLachlan, 1996; Posey et al., 1996). This change in sediment structure may have precluded faunal recolonization of the intertidal habitat following the disturbance event.

The benthic macrofauna recorded during these surveys are intertidal/subtidal species, observed in the wet sand above swash zone, swash zone, and/or subtidal zones. Many of the species common along the upper Texas coast have direct development (peracarids such as Haustoriidae and *Ancinus depressus*) or benthic larval stages (i.e. polychaetes *Scolelepis squamata* and *Lumbrineris*). Only a few benthic macrofauna recorded have planktonic larvae (i.e. *Donax* spp. and *Emerita portoricensis*). The macrofaunal species present after the hurricane (Haustoriidae, *S. squamata*¸ *Lumbrineris* sp, *Donax* sp., *E. portoricensis*, and *Callichirus islagrande*) all have larval stages that are either benthonic or direct development with the exception of the one *E. portoricensis* and one *C. islagrande* recorded at only one beach and *Donax* spp. The two most common and abundant taxa after the hurricane, Haustoriidae and *S. squamata*, are organisms which are associated with disturbance and may be also found subtidally (Keith and Hulings, 1965; Croker and Hatfield, 1980; Jaramillo et al., 1987). It is possible before the storm for individuals to move into deeper waters. Because of the dramatic decrease in abundance of all taxa, most likely the macrofauna was displaced along with the sediment. It is possible that they were either buried in offshore sandbars or desiccated within the sediment as it moved onshore with the overwash. Haustoriidae and *Lumbrineris* sp. were the only taxa commonly found whose decrease in abundance was not found to be statistically significant. Haustoriidae's chitinous exoskeleton, larger size and better mobility may lend to its better survival. *Lumbrineris* sp. was not present in large numbers before the storm (Table 5.2). This similarity was responsible for the lack of statistically significant differences. The second of the most abundant species has been noted to be sensitive to sedimentation as found in a nourishment study by Bishop et al. (2006). During that study it was found that the deposition of 4 cm of sediment greatly depressed macrofaunal numbers including spionids polychaetes including *S. squamata*. During Hurricane Ike, 50 cm of intertidal sediment was lost and deposited elsewhere. Because of the significant loss of sediment initial recolonization of the beach would come from subtidally-displaced survivors not buried or lateral immigration of adults swept in from other area beaches. Repopulation of the beach is expected to source from the species initially present, new arrivals deposited via longshore transport, and from planktonic species (Grassle and Grassle, 1974; Jaramillo et al., 1987; Speybroeck et al., 2006).

Although the alteration of zonation patterns before and after the hurricane was not statistically significant, changes in patterns was observed. Croker (1968) found that Haustoriidae amphipod zonation was not affected by hurricanes. This was not the case for Hurricane Ike and the upper Texas coast as Haustoriidae preference for the high intertidal zone disappeared after the hurricane. Seasonal zonation preference for *Scolelepis squamata* appeared to be the within the swash zone. After the hurricane their numbers were greatly depressed with no zonation apparent. The hurricane immediately altered the community structure along the upper Texas coast reducing both populations and loss of zonal preference. Zonation along the beach face has been noted to be correlated to physical parameters, competition, and food availability (McLachlan, 1980; McLachlan and Jaramillo, 1995; Rodil et al., 2006). The changes in the physical environment from the hurricane not only caused a reduction in abundance among the taxa but a change in apparent zonation pattern. Reduction of abundance reduced the competition between taxa and loss of substrate most likely changed the immediate food availability.

5.4.3 Conclusion

Increased frequency of pulse disturbance events can have damaging effects on coastal ecosystems. Reduction of macrofauna was similar to the seasonal effects seen in summer to winter counts but more depressed, as noted in other studies (Barnett, 1981; Dreyer et al., 2005). Recorded abundance numbers during the summer months (June-September) were higher in comparison to the winter months (January-February) along the upper Texas coast and other intertidal sites (Croker and Hatfield, 1980; Bender et al., 1984; Shelton and Robertson, 1981; Degraer et al., 1999; Witmer unpublished data) (Table 5.3). The depressed abundance numbers appearing before the typical winter abundance decline may further depress 2009 winter abundance means, increasing recovery time. Timing of pulse disturbance events may have an effect on recolonization and the frequency of these events could dictate the type of species found (Sousa, 1984). Understanding the recovery and length of time needed for an ecosystem to return or create a new stability regime is crucial in predicting the environmental sustainability of the coast. Pulse disturbance events may have both short and long term effects on the coastal ecosystem, altering populations and changing the rate and/or magnitude of ecological resilience (Dobbs and Vozarik, 1983; Yeo and Risk, 1979; Davis et al., 2004; Defeo and McLachlan, 2005).

The continued influence that the Hurricane Ike event will have on upper Texas beach intertidal macrofauna will be examined in future studies. Predictions for recovery vary because of continuing anthropogenic manipulation of the beaches. This real time data may provide an insight into the future of the beaches, their inhabitants and resiliency.

CHAPTER VI

RECOVERY AND RESILIENCE ON THE UPPER TEXAS COAST: A CASE STUDY OF THE EFFECTS OF HURRICANE IKE

6.1 Introduction

Disturbance events can change a community, changing the physical habitat, organismal abundance, and community structure (Hayes, 1967; Copeland, 1970; Sousa, 1984; Ebeling et al., 1985; Morton and Sallenger, 2003; Bishop et al., 2006). Dynamic communities are better adapted to handle disturbance events and usually include primary and secondary successional organisms (Dauer and Simon, 1976; Thistle, 1981; Sousa, 1984; Jaramillo et al., 1987; McLachlan et al., 1996). The ability of a community in a disturbed habitat to rebound or recover to the previous or new state is its resilience (Holling, 1973). Recovery in communities varies greatly dependent upon the level of disturbance event. Coastal environments have been studied in their recovery ability from to storms, human projects, and natural erosional events (Boesch et al., 1976; Jaramillo et al., 1987; Morton et al., 1994; Moffett et al., 1998; Schoeman et al., 2000; Gibeaut et al., 2002; Peterson et al., 2006; Speybroeck et al., 2006).

Open sandy beaches along the Gulf coast are exposed to seasonal storms which cause havoc on coastal communities and species diversity (Saloman and Naughton, 1977; Jaramillo et al., 1987; Davis et al., 2004; Dryer et al., 2005). In a moderately disturbed environment one may expect to find the greatest species richness (Petraitis et al., 1989). The sandy beach is a harsh environment where conditions of daily tides, winds and waves beat against the shoreline. Organisms with the ability to endure a wide range of physical elements and a variety of food sources may be best suited for such an environment. Sandy beaches are species poor habitats (McLachlan and Brown 2006). The few species present on sandy beaches are well adapted occurring in great abundance at preferred zones. Storms have an ability to cause change in dynamic systems such as sandy beaches.

Recovery in disturbed ecosystems can vary (Hayes, 1967; Jaramillo et al.,1987; Petraitis et al., 1989; Morton et al., 1994; Valiela et al., 1998; Morton and Sallenger 2003; Stone et al., 2004). Some many not fully recover but find a new equilibrium/resilience or regime shift (Sousa, 1979; Yeo and Risk 1979; Jaramillo et al.,1987; Scheffer et al., 2001; Folke et al., 2004; Gardner et al., 2005; Hughes et al., 2005). Recovery of an ecosystem can take hours (i.e. water chemistry) (Davis et al., 2004), months (Saloman and Naughton, 1977; Peterson et al., 2000) or even years if the sediment is severely altered or removed (Boesch et al. 1976; Jaramillo et al., 1987; Morton et al., 1994). Ecological resilience suggests that there may be varying levels of resilience and the adaptive capacity, movement between them can be caused by a stressor or disturbance (Gunderson, 2000). The ability of an ecosystem to recover may be within its own extreme fluctuations as the amount of stress and species composition within a community has much to dictate in recovery (Allison, 2004). Sampling within patchy communities can be problematic as they only provide a snapshot of the community makeup. Paine and Levin (1981) noted that only in the entirety (amalgamation) of this patchiness could one determine the true “community mosaic”, ecosystem inhabitants. They also noted that as recovery continues, establishment of varying species may affect later colonization. This variation may change the "mosaic", creating an alternative stable state. Measuring resilience or determining regime shift without longterm detailed data on the community structure would be problematic (Holling, 1973).

The upper Texas coast experiences many types of disturbance events including natural erosion, hard structure construction, beach nourishment, and storms. Because of these events many organisms found on open sandy beaches are early successional. In September 2008, Hurricane Ike made landfall on Galveston Island causing great disturbance to the nearby sandy beaches (see Chapter VI). This chapter reviews intertidal macroinfaunal data gathered during the recovery period after Hurricane Ike, from September 2008 through May 2009. Geological and biological data were examined to determine amount of recovery and state of resilience along the coastline. As the Texas coast experiences regular tropical storm disturbances at a rate of one every 0.76 years (McGowen et al., 1977; app A), these disturbances provide an opportunity to examine the plasticity and resilience of a dynamic ecosystem.

6.2 Materials and methods

6.2.1 Study sites and design

Four study sites were selected based on low to moderate use, site accessibility, and position along the upper Texas coast. Sites were named by the nearest municipality. From northeast to southwest the sites included Sabine Pass, High Island, Jamaica Beach, and Surfside Beach (Fig 6.1). Each site was surveyed monthly within 10 days of the full moon. Surveys included recordings of beach profiles, sediment size, and macrofaunal densities.

Two shore normal transects were established at each beach demarked by a stationary object (benchmark) and fixed by GPS coordinate. The benchmark established at each beach at the beginning of the study before Hurricane Ike were reestablished after Hurricane Ike using GPS coordinates, confirming positions with photographs, remaining landmarks and range markers. A beach elevation survey was conducted monthly by site along the “b” transect line with the established benchmark. Surveys ran from the benchmark to the shoreline including 5 m into the intertidal zone. The LaserMark LMH series, laser survey equipment, was used to determine elevation throughout this project. Elevation was normalized to sea level using verified data from local NOAA buoy, Galveston Pleasure Pier, TX Station ID: 8771510 for Jamaica Beach, High Island, and Sabine Pass site and NOAA buoy, USCG Freeport, TX Station ID: 8772447 for Surfside Beach. North American Vertical Datum 1988 (NAVD ’88) mean low low water mark (MLLW) was used in elevation measurements. Along each transect six intertidal stations were established for macrofaunal coring and used in determination of zonation (Fig. 6.2).

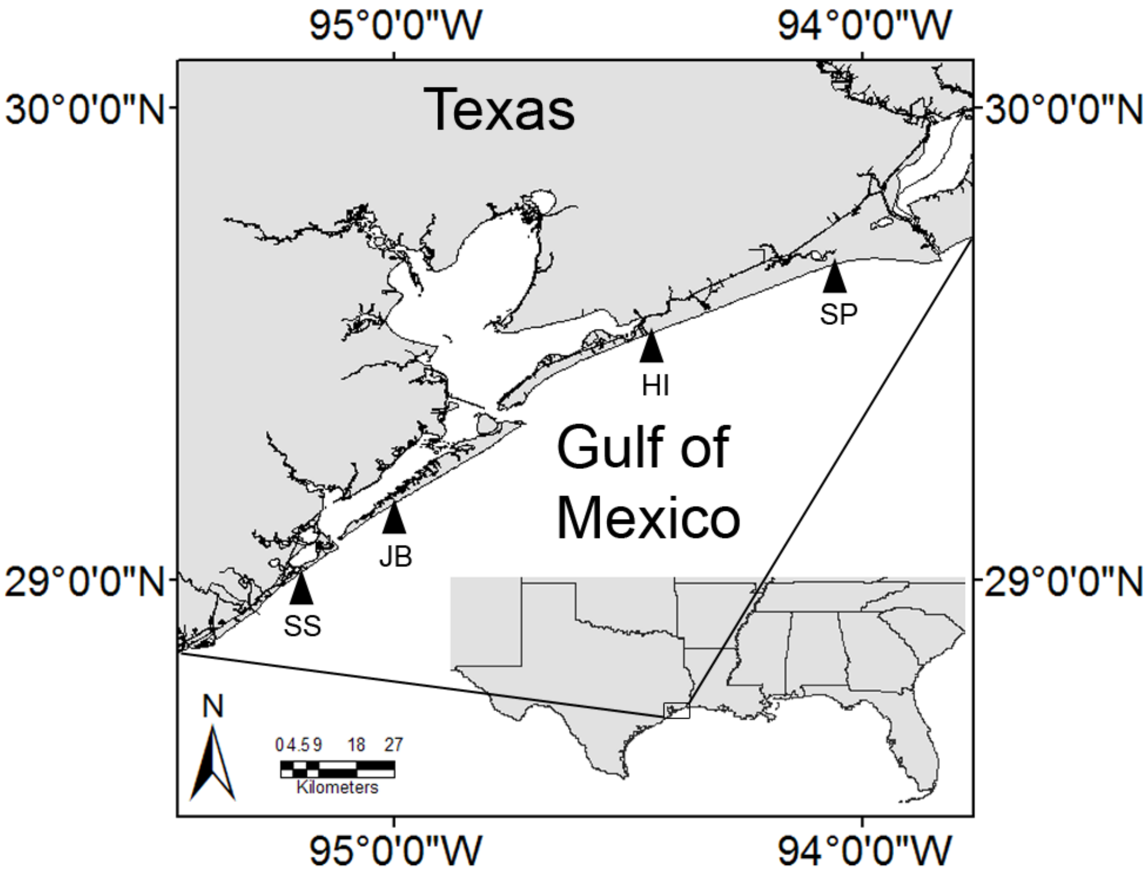

Fig. 6.1. Study sites. Location of each study site, titled by nearest municipality. SP- Sabine Pass; HI- High Island, JB- Jamaica Beach; SS- Surfside Beach.

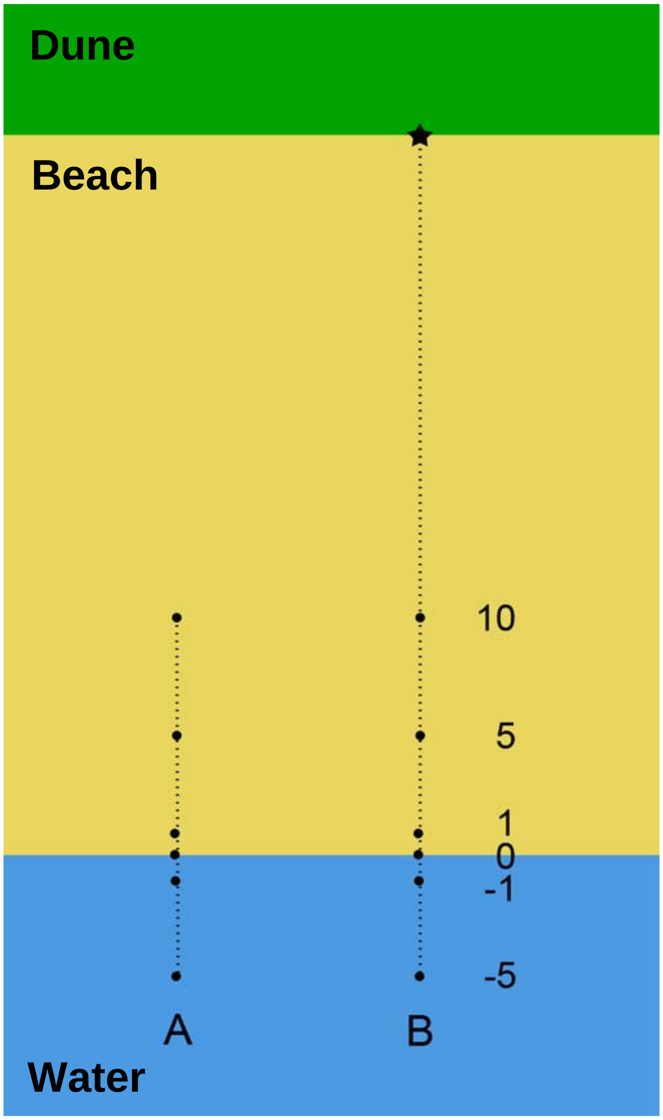

Fig. 6.2. Beach survey experimental design. Shore normal transects A and B are shown along with the 6 macrofaunal station ranging from -5 to 10 m outside relative sea level, designated by “0”. The star designated the established GPS benchmark.

6.2.2 Sediment analysis

Sediment was collected during the summer and winter each year from each site and after Hurricane Ike, five collections total. Three 10 cm diameter by 10 cm length cylindrical cores taken in 2008 extended from the subtidal zone to just outside the swash

(-5 m, 0 m, 5 m). Sediment sample collected after Hurricane Ike was at the 0 m station only. For comparison, values from the 0 core were used to determine beach type and comparison against macrofauna detected. Sediment was placed in Ziplock bags for transport. In the laboratory sediments were dried at 35 °C in a Thelco Precision Scientific oven until a constant weighed was obtained (ASTM, 2002; Eleftheriou and McIntire, 2005). A randomly selected 25 g sample was placed on top of six nested sieves for sorting using a RO-TAP Testing Sieve Shaker, WS Tyler Company for 15 minutes. Sieves ranged from 2.0 mm to <0.063 mm with each Wentworth size class represented: 2.0 mm (gravel), 0.6 mm (coarse sand), 0.25 mm (medium sand), 0.125 mm (fine sand), 0.063 (very fine sand), < 0.063 mm (silt and clay fraction). Physical measurements such as salinity, temperature (water and air), wind speed/direction, wave height (following procedures described in Bascom, 1964), tide, swash length, and weather conditions were also taken at each site.

6.2.3 Macroinfauna

Monthly intertidal core samples were collected at each site every 4 weeks; total of 48 cores. Each site had six intertidal stations with two transect replicates. The sediment core was a cylindrical PVC tube measuring 10 cm diameter by 10 cm length (0.00785 m^2). Total surface area collected monthly was 0.0942 m^2 per site or 0.3768 m^2 total across all sites.

Sediment cores were sieved with a 1.0 mm bucket sieve on site with the remaining sieved particles fixed and temporarily preserved 10% formalin pre-stained with Rose Bengal until sorting in the laboratory at Texas A&M University, College

Station, Texas. In the laboratory specimens were sorted from shell fraction and debris, then identified and counted. Identified specimens were stored in 95% ethanol. Identification was made to the lowest possible taxonomic level. List of macrofauna identified and resources used for identification may be found in Appendix C. Other data collected included major shell presence, wrack line location(s), debris and any other relevant biota identification/notes.

6.2.4 Statistical analyses

Multiple analyses were conducted on the recovery data set, using diversity, univariate and multivariate techniques. Data were sorted to identify and remove pelagic taxa from the data set. Measurements of diversity were conducted on the benthic survey data. Diversity indices used include richness (S), Shannon-Weiner diversity index (H') and Simpson's evenness (E). Analysis was conducted in Microsoft EXCEL with diversity analysis add-in from University of Reading, United Kingdom. Because of missing (zero) values and lack of normality, non-parametric measures were used for site and station comparison analysis. Both a and b raw data transects were examined using Kruskal-Wallis tests with Mann-Whitney posthoc. High Island was removed from the site comparison analyses because of consistent divergent biological and geological differences and was statistically significantly different from the other sites. Correlation analysis was conducted using monthly physical measurements. Physical and biological analyses were conducted using SPSS version 16.0. Graphs were created using Microsoft EXCEL 2007. Sediment analysis was conducted in Excel 2007, using GRADISTAT version 4.0, Blott 2000. P-values were considered statistically significant at 0.05 level.

Because of use of non-parametric tests, p-values were considered of statistical interest between 0.1 to 0.05 level.

6.3 Results

6.3.1 Geomorphic recovery

The geology and physical aspects of an environment may vary along a coastal environment, creating a dynamic community habitat. The upper Texas coastal environment experienced a violent upheaval because of the strong winds and waves from Hurricane Ike. Notable changes after the storm included sediment grain size change by at least one Wentworth category (i.e. fine sand to medium sand), decrease in slope, and decrease in elevation (loss of sediment). The recovery period saw a return of many of these to previous levels although the sites recovered differently. Six physical measurements were taken monthly, water temperature, air temperature, salinity, wave height, swash range, and slope. These did not differ significantly between sites after the hurricane as recorded during the baseline study (Table 6.1). During the nine month sampling period it was found that the only measurements to differ significantly from September 2008 to May 2009 were salinity, wave height and swash range ($p=0.020$, 0.018, 0.017 respectively). Seasonality was recorded because several measures were found to be statistically significant different from winter (January-February 2009) to spring (May 2009) (Table 6.1). Air and water temperature was found to be significantly correlated ($p=<0.001$) along with salinity to air and water temperature ($p=0.005$, 0.001). Swash range and wave height was also found to be correlated ($p=<0.001$). Examination of physical correlations by site showed that at Surfside Beach slope was correlated to swash range (p=0.026) and High Island slope was correlated to wave height (p=0.018). The physical measurements were not found to differ significantly between the baseline and recovery datasets by seasons and months. Beach width, as defined from the benchmark (dune line before Hurricane Ike) to the high tide line, after the hurricane had decreased from the previous month. The amount of beach face lost (landward movement of high tide) by study site was: Sabine Pass 7 m; High Island 8.76 m; Jamaica Beach 34.7 m; Surfside Beach -3.2 m. These values lengthened over the winter but by May only Sabine Pass site returned to near summer 2008 values (Sabine Pass 22.97 m; High Island 15.13 m; Jamaica Beach 22.76 m; Surfside Beach 29.33 m). The High Island study site exhibited continued decreasing beach width and landward migration of sea level.

Profile data showed the recovery of the study sites after the normal winter storms (Fig. 6.3). Sand removed from the beach face during the hurricane showed some evidence of return based on the increasing elevation at each study site. Elevation at both Jamaica Beach and Sabine Pass was found to increase during the 9 months recovery period. Surfside Beach did exhibit some recovery as noted by return of grain size and accumulation of sediment but an increased flattening of the beach was observed during the 9 month recovery period. High Island did experience an increase in sediment as observed in the increase of elevation. But the profile during May was lower in elevation than in April. As sites varied by physical influences and human manipulation, physical recovery of the beaches also varied.

Table 6.1. Summary statistics of physical measures at study sites along the upper Texas coast from September 2008 to May 2009 (summer vs. winter). Mean/standard deviation of seasonal data: a.) September 2008; b.) winter includes months of January and February, some do not include standard deviation as only January data was taken; c.) summer data was the month of May only. *= of statistical interest. **= statistically significant.

a.

September 2008 Study Site	Water temp (°C)	Air temp (°C)	Salinity	Waves (m)	Swash range (m)	Slope (°)	Beach width (m)
Sabine Pass	27	27	23	0.15	4	1.46	14.7
High Island	25	29	25	0.15	2	1.18	5.14
Jamaica Beach	27	27	26	0.30	2	1.63	-13.4
Surfside Beach	26	26	23	0.30	4	0.93	32.4
p-value (df=3)	0.39	0.39	0.39	0.39	0.39	0.39	0.39

b

Winter Study Site	Water temp (°C) (mean±SD)	Air temp (°C) (mean±SD)	Salinity (mean±SD)	Waves (m) (mean±SD)	Swash range (m) (mean±SD)	Slope (°) (mean±SD)	Beach width (m) (mean±SD)
Sabine Pass	17.00 ±1.41	19.00 ±1.41	28.50 ±0.71	0.30 ±0.00	3.00 ±1.41	1.81	25.44
High Island	16.00 ±2.30	18.50 ±0.71	27.50 ±2.12	0.46 ±0.22	3.50 ±0.71	2.00	-1.44
Jamaica Beach	14.00 ±1.34	17.00 ±1.41	27.00 ±2.82	0.48 ±0.03	5.50 ±4.95	1.05 ±0.13	15.3±8.06
Surfside Beach	16.00 ±2.17	17.50 ±2.12	27.50 ±2.12	0.55 ±0.08	5.00 ±1.41	1.00 ±0.15	59.90
p-value (df=3)	0.53	0.52	0.93	0.29	0.69	0.27	0.28

c.

Summer (May only) Study Site	Water temp (°C)	Air temp (°C)	Salinity	Waves (m)	Swash range (m)	Slope (°)	Beach width (m)
Sabine Pass	26.00	28.00	21	0.46	10	1.39	19.44
High Island	26.00	27.00	19	0.46	10	2.01	-18
Jamaica Beach	23.00	32.50	20	0.60	10	1.51	11.4
Surfside Beach	26.00	28.00	22	0.60	17	0.63	45.7
p-value (df=3)	0.39	0.39	0.39	0.39	0.39	0.39	0.39
p-value between seasons (df=1)	0.006**	0.006**	0.006**	0.38	0.006**	0.670	0.327

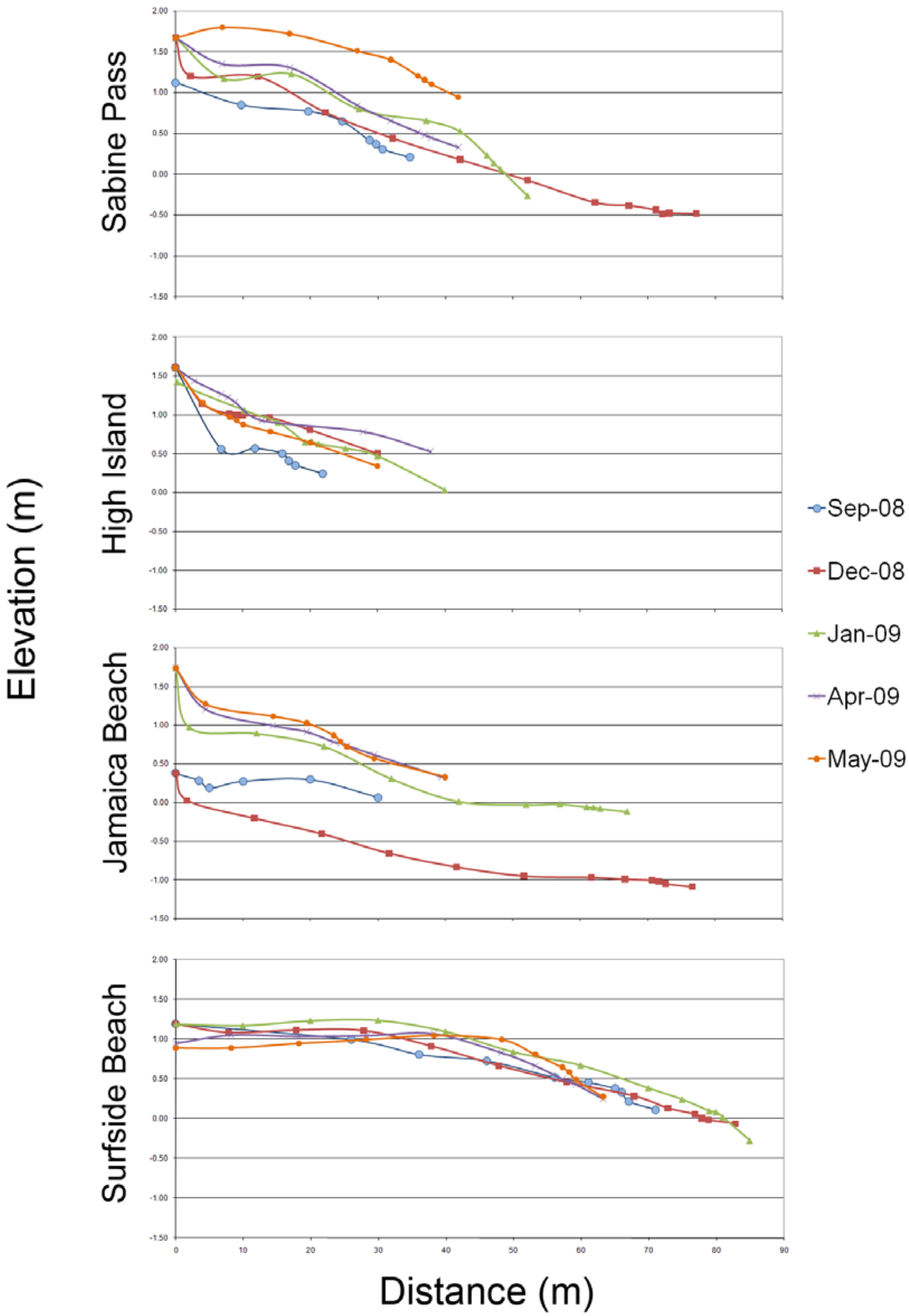

Fig. 6.3. Beach profiles of selected months from the four study sites along the upper Texas coast. Months were selected were based on seasonality and selective relevance.

6.3.2 Biological recovery and resilience

During the nine month survey following Hurricane Ike, 3,995 individual benthic specimens were counted from 16 taxa. The overall Shannon-Weiner Diversity index was measured at 1.09 with an evenness value of 0.39. Shannon's Diversity by season after Hurricane Ike was measured at 1.93 (0.59 evenness) during the winter (January and February 2009) and 0.78 (0.28 evenness) during the month of May. The six most abundant and common taxa along the upper Texas coast as identified during the baseline study (Chapter V), *Scolelepis squamata*, *Lumbrineris* sp., Haustoriidae, *Ancinus depressus*, *Donax* spp., and *Emerita portoricensis*, made up 95.62% (3,820 specimens) of the total individual benthic specimens found during the nine month study. The top two taxa, Haustoriidae and *Scolelepis squamata*, made up 82.78% (3,307 specimens) of the total benthic specimens identified with Haustoriidae making up 68% (2,729 specimens) of the total benthic taxa while *S. squamata* made up 14.47% (578 specimens).

The six most abundant taxa after Hurricane Ike included five of the most abundant and common taxa identified during the baseline study: *Scolelepis squamata*, *Lumbrineris* sp., Haustoriidae, *Ancinus depressus*, and *Donax* spp. (Table 6.2). The sixth taxon identified as most abundant after Hurricane Ike, Corophiidae, was abundant but not as common as it was only encountered during the fall/winter. Corophiids were found to occur in greater numbers at High Island, a site devastated by the hurricane. The excluded taxon from the baseline's top six abundant/common taxa list, *Emerita portoricensis*, was not as prolific during the recovery data set because this species tends to occurs in greater number during the summer which was not included in this nine month survey. The three most abundant taxa found during the baseline study, Haustoriidae, *S. squamata*, and *Donax* spp., were also the three most abundant taxa found during the recovery study (Table 6.2). Although juvenile Arcidae were found in high numbers, they are not included in the abundant and common list because they were only encountered during one month. Two taxa ranked overall in the ten most abundant taxa list were not found during the recovery study. In the recovery study the sixth most abundant taxon was *Orchestia* sp. It was not abundant enough to make the ten most abundant taxa as it was identified to occur in the intertidal zone during the fall and winter at all zonal levels (Table 6.2).

Table 6.2. Ten most abundant taxa from baseline (Chapter V) and recovery study. Baseline data was taken July 2007 through August 2009. Recovery data was taken September 2009 through May 2010. Rank is based on abundance.

Taxa	**Total**	**Baseline study**				**Recovery study**			
	Rank	*Rank*	*Total #*	# Sites	# months	*Rank*	*Total #*	# Sites	# months
Haustoriidae	1	1	14918	4	15	1	2729	4	9
Scolelepis squamata	2	2	10607	4	15	2	578	4	9
Donax spp.	3	3	1206	4	14	3	411	4	8
Juv. Arcidae	4	4	290	3	1	0	0	0	0
Emerita portoricensis	6	5	201	4	8	9T	12	3	6
Ancinus depressus	5	6	164	4	11	5	62	4	4
Lumbrineris sp.	7	7	99	4	14	7	27	4	9
Petricola sp.	10	8	43	2	2	0	0	0	0
Alymyracuma sp.	9	9	33	3	6	8	18	3	3
Austinixa beherae		10	12	3	5	9T	12	1	5
Corophiidae	8	16	5	3	5	4	92	3	5
Total numbers			**27639**	**4**	**15**		**3995**	**4**	**9**

Abundance after the storm was drastically reduced with some sites being decimated, i.e. High Island site. During the month of October a minor growth in overall abundance was observed (Fig. 6.4) before the winter cooling took effect reducing the population below previous winter abundance numbers ($p=<0.001$) (Table 6.3). This varied by site with Jamaica Beach and Surfside Beach exhibiting statistically significant winter differences ($p=<0.001$, 0.003 respectively). Overall growth in abundance was observed from winter to May 2009, the end of the study, although the increase was attributed to only one site, Sabine Pass (Fig. 6.4). The rate of change was calculated for each site September 2008-May 2009: Sabine Pass 4.03%, High Island 0.10%, Jamaica

Beach 2.19%, Surfside Beach 0.32%. Upon further examination, the rates of growth in abundance during the spring time, January-May 2008, from the baseline data (Chapter V) at Sabine Pass (5.82%) and High Island (0.79%) were found to be similar to the recovery data set, January-May 2009 (Sabine Pass 3.73%, High Island 3.62%). These were the only sites that were similar. Jamaica Beach, and Surfside Beach (20.51%, 13.35% respectively in the baseline study) each experienced negative abundance growth rates (Jamaica Beach -0.05% and Surfside Beach -2.34%). The Sabine Pass site was the least human manipulated because it was remotely located. High Island was decimated because all the sediment was removed by the hurricane. Growth here was inherently positive. Jamaica Beach experienced a great sediment and organism loss after the hurricane. Recovery at Jamaica Beach varied during the recovery. Initially there was some recovery of organisms but this progress was reversed with beach cleanup and traffic. Some recovery of sediment and organisms after the cleaning was evident. Surfside Beach experienced a continued loss of abundance as the beach experienced heavy traffic because of the loss of the road previously located behind the beach area. Analyses of abundance by seasons and months were conducted within and between the sites. It was found that the recovery data abundance counts were not statistically different from September 2008 to May 2009. When examined by site statistical significance varied. Statistically significant differences were found at Sabine Pass in *Scolelepis squamata*, Haustoriidae, *Donax* spp. and abundance (p=0.007, <0.001, 0.003, <0.001 respectively); High Island by *S. squamata* and total abundance (p=0.033, 0.001 respectively); Jamaica Beach by Haustoriidae and total abundance (p= 0.019, 0.006

respectively), and Surfside Beach by *Donax* spp. and total abundance (p=0.008, 0.004 respectively). The overall site comparison between the winter (January and February) and spring (May 2009) was found to only be statistically different by the *Donax* spp. counts. This varied by site: Sabine Pass - Haustoriidae, *Donax* spp. and abundance (p=0.004, <0.001, 0.003 respectively); High Island - *Lumbrineris* sp. and abundance (p=0.012, 0.001 respectively); Surfside beach - Haustoriidae and abundance (p=<0.001 for both respectively); no significance for Jamaica Beach. An annual comparison revealed statistical differences between the baseline winter (January and February 2008) and recovery winter (January and February 2009) data sets (Table 6.3a). It also revealed statistical differences between the baseline summer (June-August 2007) and recovery late spring (May 2009) data sets (Table 6.3b). Examining the previous year's data by month, May 2008 to May 2009, abundance was similar to the previous summer comparisons (Table 6.3c). The combined overall data set showed statistically significant differences for *S. squamata*, *Lumbrineris* sp., Haustoriidae and abundance (p=0.002, 0.021, <0.001, <0.001 respectively). May 2008 to May 2009 analysis by site differed from the combined data set. Statistical significance was detected at Sabine Pass by *Lumbrineris* sp. and *Donax* spp. (p=0.032, 0.039 respectively); Jamaica Beach by *S. squamata*, Haustoriidae, *Donax* spp. and abundance (p=0.003, 0.001, 0.008, <0.001 respectively); Surfside Beach by *S. squamata*, Haustoriidae, *Donax* spp. and abundance (p=0.002, <0.001, 0.009, <0.001 respectively) but no significances were detected at High Island.

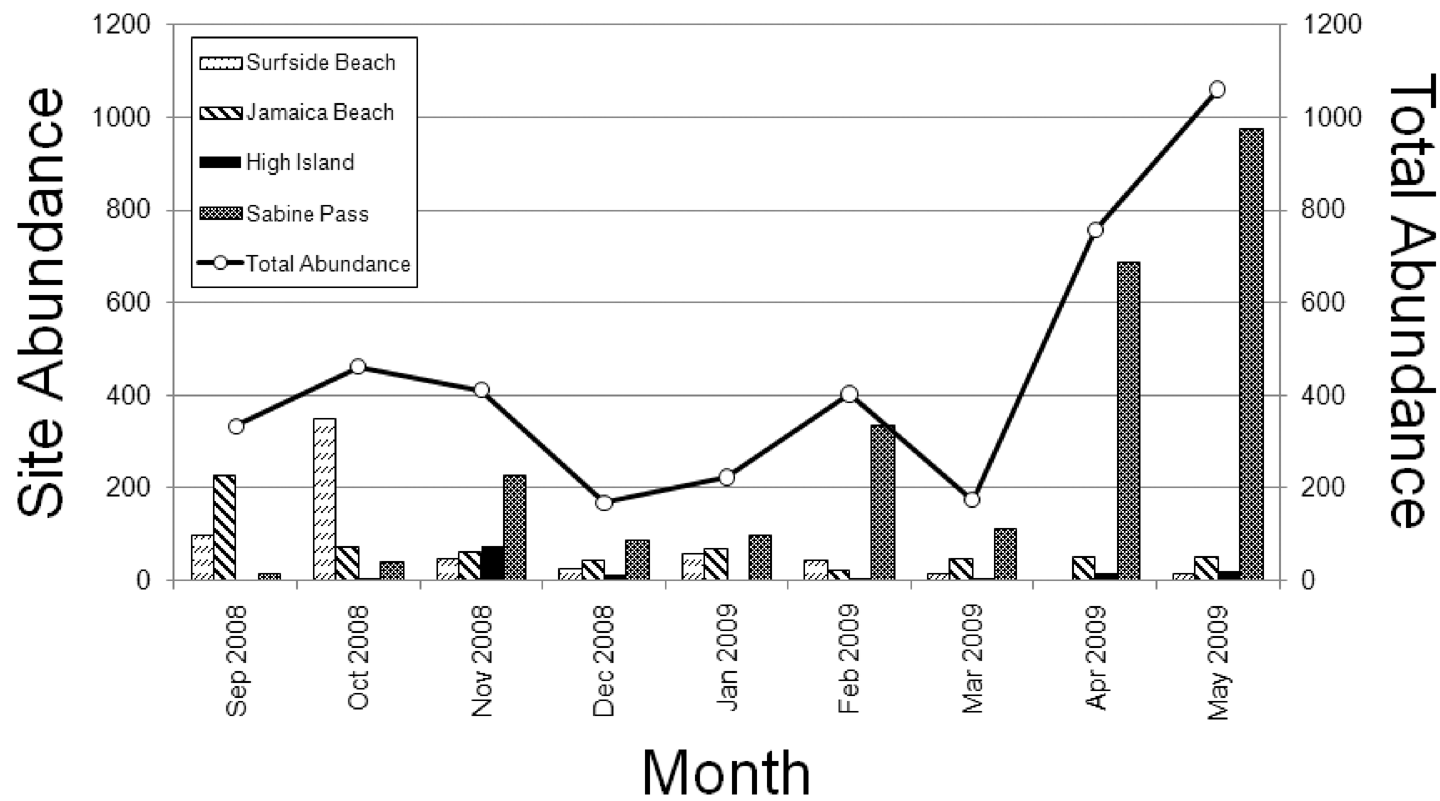

Fig. 6.4. Intertidal macrofaunal abundance across all taxa by month and site along the upper Texas coast. Y axis denotes site abundance counts. Secondary Y axis denotes total abundance counts over all sites.

Table 6.3. P-values for total abundance and top six taxa. Values from Kruskal-Wallis tests on seasonality from raw data. a.) winter 2008, 2009; b.) summer 2007, 2009; c.) summer 2008, 2009. Overall tests excluded High Island values. Degrees of freedom=1. *= of statistical interest. ** = statistically significant.

a.

Win 08,09	N	*Scolelepis*	*Lumbrineris*	Haustoriidae	*Ancinus*	*Emerita*	*Donax*
Overall	<0.001**	0.079*	0.518	0.001**	0.062*	0.353	0.194
Sabine Pass	0.114	0.004**	0.480	0.138	0.003**	1.0	0.004**
High Island	<0.001**	0.003**	1.0	0.317	1.0	1.0	1.0
Jamaica Beach	<0.001**	0.004**	0.586	<0.001**	1.0	0.386	0.656
Surfside Beach	0.003**	0.005**	1.0	0.009**	0.386	0.453	0.444

b.

Sum 07, 09	N	*Scolelepis*	*Lumbrineris*	Haustoriidae	*Ancinus*	*Emerita*	*Donax*
Overall	0.002**	0.005**	0.013**	0.845	0.086*	0.729	0.002**
Sabine Pass	0.022**	0.400	0.232	0.005**	0.407	0.407	0.224
High Island	0.056*	0.789	0.074*	0.195	0.480	0.207	0.122
Jamaica Beach	<0.001**	<0.001**	0.019**	0.608	0.076*	0.733	0.001**
Surfside Beach	0.002**	0.108	0.480	0.002**	0.157	0.310	0.010**

c.

Sum 08,09	N	*Scolelepis*	*Lumbrineris*	Haustoriidae	*Ancinus*	*Emerita*	*Donax*
Overall	<0.001**	<0.001**	<0.001**	0.004**	0.512	0.006**	0.095*
Sabine Pass	0.537	0.040**	0.545	0.153	0.282	0.282	0.001**
High Island	0.322	0.059*	0.329	0.013**	0.409	0.178	0.409
Jamaica Beach	<0.001**	<0.001**	0.045**	0.042**	0.112	0.217	0.291
Surfside Beach	<0.001**	<0.001**	0.004**	<0.001**	0.733	0.013	0.248

Taxa abundance was greatly reduced after the hurricane. September 2008's total abundance was 13% of the counts found during the August 2008 survey. A slight increase in numbers was observed in October 2008 led by the two dominant taxa, Haustoriidae and *Scolelepis squamata*, but this was heavily influenced by one site, Surfside Beach, whose abundance later plummeted (Fig. 6.5). Winter senescence followed with the abundance numbers that were lower than the previous year. A rebound in abundance was seen in late spring, influenced by the haustoriid amphipods. Haustoriidae species was the only taxon of notable observance each month (Fig. 6.5). The second most dominant taxon, *S. squamata*, was observed just after the storm disturbance but decreased greatly until spring. This taxon has been observed in the past to increase in abundance during the summer just after the amphipods. Data from the community analysis project showed an increase in *S. squamata* during June 2009 data at Jamaica Beach. A comparison of the three years of data from Jamaica Beach show distinct differences between the three years (Table 6.4). June 2009 does exhibit depressed numbers, but improvement from the winter 2009 data set.

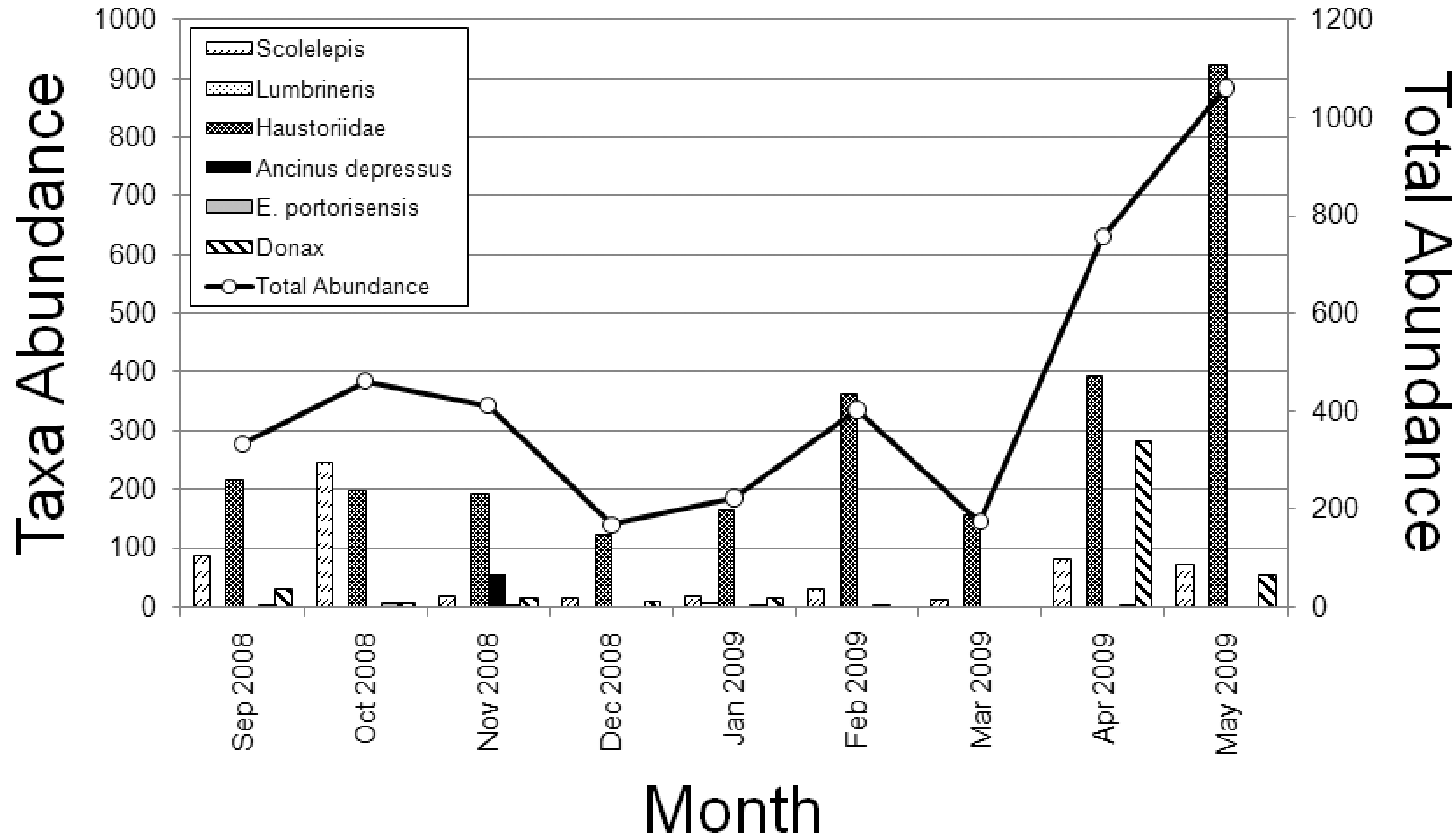

Fig. 6.5. Most common six intertidal taxa abundance by month across all study sites along the upper Texas coast. Y axis denotes taxa abundance counts. Secondary Y axis denotes total abundance counts over all sites.

Table 6.4. Abundance counts at Jamaica Beach during June of each year. Mean and standard deviations are given.

Year	*Scolelepis squamata*	*Lumbrineris* sp.	Haustoriidae sp.	*Ancinus depressus*	*Emerita portoricensis*	*Austinixa beherae*	*Donax* spp.	Abundance	Richness
2007	106 ±48.1	0±0	91±34.6	0±0	0±0	0±0	23±0.7	220±82.7	3
2008	453±55.2	2±0.7	421±72.8	0±0	2±2.8	0±0	1±0.7	878±126.6	4
2009	31±19.1	0±0	63±4.2	2±0.7	2±1.4	1±1.4	3±0.7	101±22	6

Zonation during the baseline study (Chapter V) was divided into four identifiable zones from the six stations. Stations were identified as follows: -5 = low intertidal/subtidal; -1, 0, 1 = lower mid-intertidal/swash zone; 5 = mid-intertidal; and 10 = high intertidal. Because of the reduction of total abundance and taxa, zonation along the upper Texas coast varied. High Island experienced a loss of organisms after the storm. During the following nine months, *Scolelepis squamata* was observed occupying the mid-intertidal zone during December, February, and May. Counts of one or two haustoriid amphipods were found during the months of February to May. These were found only in the mid- and high intertidal stations. This differed slightly from the baseline because *S. squamata* was more commonly found in the swash zone. One taxon that occurred in large numbers during November alone was a corophiid amphipod. It was observed from the swash to the high intertidal zone at High Island. This taxon was observed at 2 other sites during the survey period but in very small numbers (i.e. 1 or 3). At Jamaica Beach recovery varied monthly. Numbers were observed to decrease greatly after September before a small rebound in the spring. Taxa zonation changed slightly in comparison to observations before the storm disturbance. Haustoriidae peaked in abundance in lower mid- and mid-intertidal zones except during April and May of 2009 where it peaked at the low/subtidal zone. June 2009 data showed an increase in abundance and return to baseline zonation for the haustoriids. Zonation for *S. squamata* appeared to maintain lower mid-intertidal zonation but could not be adequately determined because of its low occurrence. At Surfside Beach the zonation and taxa dwindled as recovery progressed at the other sites. During the month of October the two dominant taxa, Haustoriidae and *S. squamata*, were observed in numbers more than five times greater than from the previous month. This surge in numbers did not continue, but reduced to counts below that of September2008 when just after the storm for the duration of the study. Only a few *S. squamata* were observed after October, Haustoriidae were observed at all zonal levels (Fig. 6.6). The last study site, Sabine Pass, experienced the greatest recovery post-Hurricane Ike. Initially this site's abundance counts declined each month with the winter senescence, then, with spring growth, recovery in abundance was observed. Overall zonation appeared to be retained during the recovery period with Haustoriidae at the higher stations and *S. squamata* more abundant at the lower mid-intertidal zone.

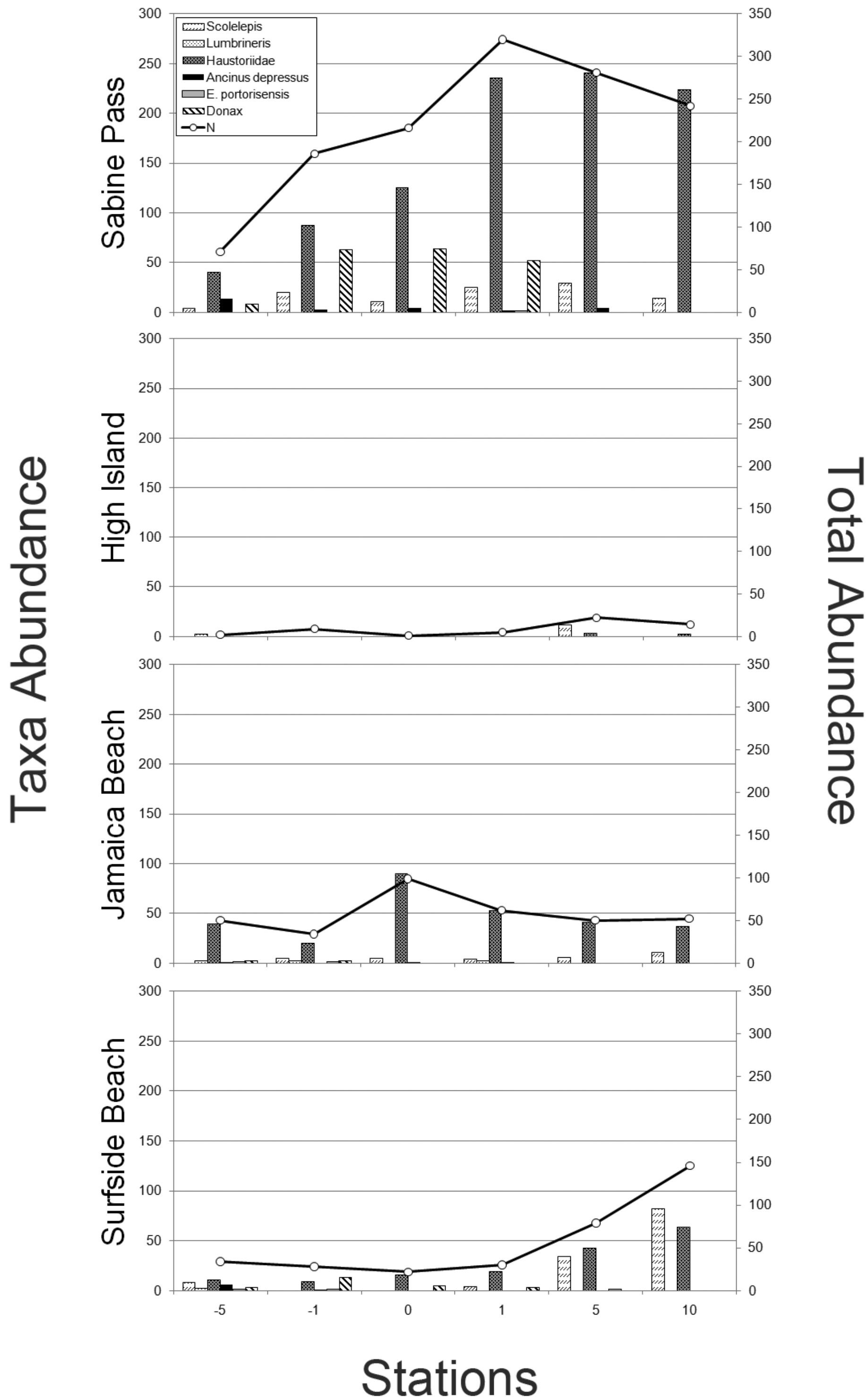

Fig. 6.6. Intertidal macrofaunal zonation at each study site along the upper Texas coast (shown separately). Y axis denotes log taxa abundance counts. Secondary Y axis denotes total abundance counts over all sites.

6.4 Discussion

Disturbances have the capacity to cause change in community assemblages and structure that was observed along the upper Texas coast after Hurricane Ike. The ability of an ecosystem to recover after such disturbance can provide insight into the ecosystem's resilience. Holling (1973) coined the term resilience as the ability of a system to experience variation and the extent of that variation. Coastlines along the east coast oscillated between normal and extreme erosion with storms, eventually recovering to their previous state (List et al., 2006). In this study the response of the benthic community along the coastline varied greatly. Although similar in habitat the intertidal benthic community was observed to undergo oscillation from one extreme, decimation, to recovery in different stages. Allison (2004) came to the conclusion each storm event or stressor affected the diversity in a community differently. The level of disturbance extruded and the species that remained in the community dictated the community response. Natural disturbances in benthic communities are common (see Sousa, 2001 for extensive reference list), especially with hurricanes along the Gulf of Mexico (Keith and Hulings, 1965; Morton et al., 1994; Posey et al., 1996; Davis et al., 2004; Stone et al., 2004). The strength of each hurricane varied greatly; expected response to those disturbances in the benthic community should reflect that same variance.

6.4.1 Recovery of beach environment

Habitats that were the least manipulated after the storm exhibited the greatest recovery. The southern sites, Surfside Beach and Jamaica Beach received moderate to great human induced disturbance after the storm. The macroinfauna decreased at both of the sites probably because of that disturbance. Surfside Beach was located on the western side of the hurricane and located >40 miles from the eye. This site initially fared well, but because of loss of road behind the dunes, the beach became the highway for reconstruction of Follet's Island. This primary use of the beach continued for nearly nine months after the hurricane, during which the survey counts continued to decline. No recovery was recorded for this site. Jamaica Beach experienced a significant loss of sediment and loss of the artificially created back beach dunes. Abundance counts here exhibited decline during beach cleanup of debris. Taxa and counts at Jamaica Beach showed positive increase during the spring after the cleanup and continued to experience some recovery by June 2009. Longshore transport of sediment from north to south could affect the amount of sediment accumulated at Jamaica Beach with beach nourishment occurring during the winter of 2008-2009. The northern sites, High Island and Sabine Pass, were located on the eastern side of the powerful hurricane and experienced little to no human manipulation after the storm. High Island located just off the Bolivar Peninsula, was decimated by the hurricane. Sediment loss was complete in the intertidal region and sargassum/sand dunes were lost. As sediment returned to this beach, it was observed to be finer than previous year observations. Large cobbles, rocks, and shells were no longer present as part of the beach sand. This allowed for a succession of individuals to initially be dominated by *Scolelepis squamata* and a corophiid amphipod. Later observances of Haustoriidae sp. and *Donax* spp. were noted. This site in the past had always been dominated by *S. squamata*. The presence of the corophiid amphipod was an uncommon observance. Longshore transport of sediment from other nearshore sandbanks or erosion from nearby beaches may also explain the decrease in sediment grain size at High Island after the hurricane. The last site, Sabine Pass, experienced loss of sediment and organisms. This site was least manipulated as it was remotely located. This study was one of the first, excluding park rangers, on this site after Ike. Sediment, taxa and counts gradually returned to this site. Because of little manipulation, winter senescence and spring growth was evident at this site. Within 3 months, sediment grain size had returned to previous state and by the completion of this survey (May 2009), much of the taxa and counts had returned.

The taxa found along the upper Texas coast are ones that have been identified as early successors as evidenced by the two most abundant taxa, *S. squamata* and Haustoriidae. During the summer months, secondary succession taxa, such as *Emerita* and *Donax*, have been noted to occur. Thistle (1981) found that early colonizers had a planktonic larval stage, unlike what was found during this study. Many of the taxa identified before the hurricane including the two most common and abundant taxa, had benthic larval stages. This life history trait probably allowed for the quick recovery of those taxa. A rapid growth rate of sandy beach species may have also allowed for quick dominance (McLachlan et al., 1996).

6.4.2 Species diversity and zonation

Sandy beaches are noted for being species poor. Unlike a heterogeneous habitat where species diversity may increase based on distinct variability within the habitat (Tews et al., 2004), the physical characteristics of sandy beaches are fairly homogeneous. Species diversity tends to be fairly low. The beach's dynamic environment, where wave, tide and wind dominate, also tend to negatively affect species diversity in addition to negative effects from regular natural disturbances such as hurricanes. The taxa recorded on the beaches both before and after the hurricane are taxa noted for occurring in disturbed habitats (Dobbs and Vozarik, 1983; Allen and Moore, 1987; Jaramillo et al., 1987). These tend to be primary or secondary succession organisms. Taxa able to quickly inhabit a space otherwise not suited for specialized organisms requires a generalist approach. It was also noted that many of the most common taxa previously identified were found within 2 weeks of the hurricane's passage and persisted throughout the recovery study (i.e. Haustoriidae, *Scolelepis squamata*, *Donax* spp., *Lumbrineris* sp.). These taxa have been noted to occur at deeper subtidal depths with the exception of *Donax* spp. (Appendix D). Their presence after the disturbance could be from those that survived the sediment upheaval or migrated from subtidal depths or other nearshore communities. Further studies in macroinfaunal migrations before and during disturbance events would need to be conducted before a more conclusive speculation could be drawn upon.

Niche partitioning has been observed in previous studies along sandy beaches (McLachlan and Jaramillo, 1995; McLachlan et al., 1996; Degraer et al., 1999; Rodil et al., 2006). Partitioning has also been observed along the upper Texas coast (Chapter V). Much of the delineation along the Texas coast was based upon the water/sediment saturation level. Previous studies have noted varied distance to the water table outcrop for juvenile and adults individuals (i.e. ghost crabs, Milne and Milne, 1946) and swash zone conditions needed for feeding and movement (i.e. *Donax*, Trueman, 1971; *Emerita*, Efford, 1966 Jaramillo et al., 2000). Intertidal taxa previously occurring in specific zones defined by water saturation levels before the hurricane remained within those same zones with the exception for the haustoriid amphipods and *Scolelepis squamata*. These two taxa were observed to occupy all zones identified within the intertidal region with varying success. The hurricane reduced the abundance of the taxa present creating more available space in all zones. Zonation immediately after the hurricane was varied. During the first few months haustoriid amphipods could be observed in all zones, mostly dominating the upper zones. *S. squamata*, preferring more water saturated sand, continued as previously observed to occupy the stations below those dominated by haustoriids. These observations were primarily based on the Sabine Pass site because it experienced the greatest recovery. These observations support an idea that Haustoriidae may competitively exclude *S. squamata* from the upper intertidal zones. Further work on this topic may provide be understanding of competition within these taxa of sandy beach organisms. Previously observed zonation at Surfside Beach and Jamaica Beach did not return by May 2009, most likely because of continued depressed abundance counts. The June 2009 data gathered at Jamaica Beach showed greater improvement and the expected zonation at the mid-intertidal level. High Island also did not provide reliable analysis in regards to zonation because of depressed numbers.

6.4.3 Expectations of storms and sea level rise

Global climate change has been affecting the Gulf coast though an increase in sea surface temperatures, sea level rise and increased hurricane activity (Stone et al., 2004; Mann and Emanuel, 2006; Anthony et al., 2009; Yu et al., 2010). Many scientists are predicting continued and increasing hurricanes for the Caribbean (Henderson-Sellers et al., 1998; Goldenberg et al., 2001; Elsner, 2006; Kerr, 2006; Sanders and Lea, 2008). This increase in storms has the ability to interfere with the beach ecosystem through destabilizing the habitat, changing recruitment, increasing erosion, and resultant human manipulation (Hughes, 2000; Galbraith et al. 2002; Zhang et al., 2004).

The Hurricane Ike storm event created an opportunity to visualize a rise in sea level along the coastline. The immediate loss of sediment because of storm created changes in the beach width and elevation. Beach sediment loss occurred in the creation of hurricane washover fans landward or sediment loss to nearshore sandbanks. Each study site fared differently depending upon distance from the storm, location (eastern versus western side) and proximity to human development. The current annual rise in sea level at Galveston, Texas was 6.84 mm (NOAA, 2010); this is higher than the global average of 1.8 mm because of land subsidence (Anderson 2007; IPCC, 2007; BEG, 2010) . Annual shore line movement has been measured at: Sabine Pass 0.5 m; High Island 1.5 m; Jamaica Beach 1.9 m; Surfside Beach 2.4 m (BEG, 2010). The high tide at each beach after Hurricane Ike moved landward on average 11.8 m, equivalent to the shoreline expected in 9.1 years (year 2019) if sea level rise, subsidence, and erosion remain constant. Beach width, elevation, and profile did exhibit some recovery as sand lost to nearshore sandbanks returned, varied by study site (Fig 6.3). This was evident in the gradual return of beaches to near previous size and the change in nearshore sandbars. Storms have been noted to accelerate erosion along the coastline removing beach and back beach from owners. Hard structures behind a beach can accelerate shoreline erosion eventually terminating the shoreline (Chapter III; Stutz and Pilkey, 2005). Sabine Pass, High Island, and Surfside Beach were all backed by roads that were underwater during the storm and later damaged with evidence of extensive erosion at seaward edge (i.e. parallel trenches, road undercutting, upper beach tidal channels pools and channels). Stiffler and Mathewson (2009) noted this as a return, water flow erosion. Future storm events have the potential to increase erosion which may increase shoreline migration of an already eroding coastline. The eventual loss of beach face will occur when contact is made with permanent manmade structures.

6.4.4 Conclusion

Storms occurring along coastlines have been observed to modify species density and the environment (Boesch et al., 1976; Yeo and Risk, 1979; Morton et al., 1994; Posey et al., 1996). Several studies on sandy beaches have demonstrated varying patterns of recovery from destructive storm events (Morton and Paine, 1985; Jaramillo et al., 1987; Dreyer et al., 2005). Recovery of sandy beaches was often hindered by increased human use and management (Clark, 1996; Allison, 2004). Natural recovery of the beaches was observed to occur at only one study site, Sabine Pass. Within nine months of Hurricane Ike's landfall on the Texas coast, the Sabine Pass site showed near full recovery of beach geomorphology (mean sediment grain size, beach slope and elevation) and macrofaunal community structure. The ecological community identified persisted with taxa identified as primary and secondary succession organisms. Disturbance adapted organisms fare well in such environments. The extremes of habitat change caused by Hurricane Ike support the idea that this type of community had a wide ecological resilience. A typical climax community in this ecosystem was not identified. Continuing studies along this coastline may provide a better understanding of the dynamic extremes and community occurring in this ecosystem.

Knowledgeable and thoughtful management of beach ecosystems is imperative for the future (Brown and McLachlan 2002; Micallef and Williams 2002; Scapini, 2003; Schlacher et al., 2007). The landward change in shoreline position because of global sea level rise and increasing subsidence and erosion is expectedly continued (Brown and McLachlan 2002; Feagin et al., 2005; IPCC, 2007). Shorelines constrained by hard structures may suspend this landward migration resulting in the loss of beach (Galbraith et al., 2002; Griggs, 2005; Stutz and Pilkey, 2005). This loss would translate into macroinfaunal loss upon which resident and migratory birds as well as coastal fish populations depend (Leber, 1982; Peterson et al., 2006). Knowledge of beach macrofaunal diversity along the Texas coast, such as haustoriid and *Scolelepis squamata*, could be used to estimate beach health to better evaluate the upward effects of disturbance, pollution and human uses on an integral part of the coastal ecosystem, initially proposed by Allen and Moore (1987).

Beaches are a fragile ecosystem endangered by human pressures (Martinez et al., 2006; Schlacher et al., 2006). These ecosystems have shown a high natural ecological resilience (Eagle, 1975), but do not preclude the possibilities of habitat extinction and/or catastrophic community regime shift (Biggs et al., 2009). As coastal areas are being increasingly more populated, integrating human development and activities with biological conservation is necessary for sustainable beach management (Small and Nicholls, 2003; Meir et al., 2004; Campbell et al., 2009).

CHAPTER VII

CONCLUSIONS

7.1 Introduction overview

Intertidal coastlines have been a topic of interest for decades with classic studies focusing on the macrofauna of rocky intertidal beaches (Doty, 1946; Connell, 1961; Paine, 1969; Dayton, 1971; Paine, 1974). Open sandy shorelines with their less dramatic features, unrecognizable zonation, and desert-like diversity and appearance have experienced an increasing interest from biologists during the last half of the 20th century (McLachlan, 1980; McLachlan and Brown, 2006; Schlacher et al., 2008).

Storms along the coastline provide an opportunity to better understand the effects of sea level rise. Effects of sea level rise are profound, drowning islands and causing shorelines to migrate landward (Gibeaut et al. 2000; Thieler and Hammar Klose, 2000; Feagin et al. 2005; IPCC 2007). Sea level rise and subsequent erosion are expected to be exacerbated on sandy beaches (Zhang et al. 2004). The Texas coast is an excellent study site for examining the effects climate change on the biota and the beach face with tropical storms making landfall on the coastline once every two years (McGowen et al., 1977; appendix A). The upper Texas coast consists of a low lying, gentle sloping coastline (characteristic of microtidal, dissipative sandy beaches) making it susceptible to flooding and sea level rise (Gibeaut et al., 2000). Regular disturbances from daily and seasonal tidal migration also caused changes to the beach face. As observed in the literature, natural, regular, or episodic disturbances result in changes in abundance and taxa diversity (Croker, 1968; Eagle, 1975; Dobbs et al., 1983; Sousa, 1984; Jaramillo et al., 1987; Petraitis et al., 1989; Posey et al., 1996). The initial effect of storms provides a snapshot of the beach face of the future with increasing sea level rise. The recovery and resilience of the ecosystem in its attempt to return to its previous state provides an understanding of what to expect in response to the changes that are predicted with global climate change.

7.2 Purpose, hypotheses, and results/discussion revisited

The intent of this study was to evaluate the effects of seasonality and climatic events on macroinfauna within the intertidal zone. Macroinfauna along the upper Texas coast was examined during a two year study from July 2007 through May 2009 with an additional, larger community surveys occurring at Jamaica Beach alone in June 2009 and June 2010. Questions examined during this study included site that were similar geologically and biologically, and whether there were differences between northern and southern sites. This study was also interested in determining the effects of storm events upon the coastline, relating the ecology of the system to the local geomorphology. During the study eight hypotheses were examined related to the above questions. Those hypotheses and the results of those analyses follow:

H1: There were no changes in beach elevation by season.

H1a: There were changes in beach elevation by season.

Result – Reject the null, accept the alternative hypothesis. This study observed seasonal migration of elevation and slope at two study sites, Jamaica Beach and Surfside Beach.

Seasonal oscillation of elevation at Sabine Pass was not as readily identified. Elevation at High Island continued to degrade each month during baseline data set (see Chapter IV, V).

H2: There was no difference in sediment grain size by season.

H2a: There were differences in sediment grain size by season.

Result – Reject the null, accept the alternative hypothesis. Sediment grain size was observed to change by season. Larger in the winter as smaller sand grains were removed to offshore sandbars and smaller sediment grain size during the summer as sands were returned to the beach face (see Chapter IV, V).

H3: There was no difference in sediment grain size between beaches.

H3a: There were differences in sediment grain size between beaches.

Result – Reject the null, accept the alternative hypothesis. Sediment grain size was observed to be different between the beaches. High Island was observed to have the largest sediment grain size including cobble and large shells as part of the composition. Sabine Pass was observed to have the next largest grain size. Surfside Beach and Jamaica Beach had similar very fine sediment grain size. Sabine Pass, Surfside Beach and Jamaica Beach all were observed to have grain size equal to or less than 125 µm as reported by Bullard (1942) to be dominant along the upper Texas coast (see Chapter III).

were observed to have larger grain size than the southern sites. The longshore current delivering sediment to the Texas coast typically runs from the northeast to the southwest. The sediment source for the northern beaches includes the Atchafalaya River and Sabine Rivers, in which sedimentation has been reduced because of damming, etc (Anderson, 2007). The southern beaches also receive sediment from these two rivers but also have an added nearby sediment source from the Galveston Bay system. This added source allows for the southern beaches to exhibit a smaller, finer grain size. Beach nourishment has been occurring at the beaches in Galveston, Texas. The southern beaches lying south of the nourishment projects may also benefit (see Chapter IV, V).

H5: There were no changes in invertebrate richness or abundance related by changing season.

H5a: There were differences in invertebrate richness or abundance related by changing season.

Result – Reject the null, accept the alternative hypothesis. This study defined seasons as summer including July and August and winter including January and February. As temperatures, wind and waves fluctuate between summer and winter on this temperate coastline, winter senescence was observed (see Chapter V).

H6: There were no differences in species composition between beaches.

H6a: There were differences in species composition between beaches.

Result – Reject the null, accept the alternative hypothesis. This study found differences between sites even with High Island removed. Most common taxa remained statistically significantly different except for the Haustoriidae which was of statistical interest. High

Island was the most depleted site for taxa and finer beach sediments. This negatively affected the population and community structure at this site, thus giving this site an outlier status and removal from data set comparisons (see Chapter V).

H7: There was no difference in species composition between eroding and sustaining beaches.

H7a: There were differences in species composition between eroding and sustaining beaches.

Result – hypothesis invalid. Each beach was determined to be eroding at some level (BEG, 2010).

H8: There was no difference in abundance or richness after major storm (pulse) events.

H8a: There were differences in abundance and/or richness after major storm (pulse) events.

Result – Varies. Tropical storms and Category 1 hurricanes - accept the null hypothesis. Larger storms (Category 4 hurricane surge or greater) with storm surge and major sediment reworking - reject the null, accept the alternative hypothesis (see Chapter V, VI, VII).

During the late summer 2008, Hurricane Ike made landfall on the upper Texas coast. Hurricane Ike caused a great disturbance to the upper Texas coast both biologically and geologically. Macroinfauna was reduced by 87% following Hurricane Ike. Beach sediment grain size increased by at least one full Wentworth size class. All four study sites were negatively affected by Hurricane Ike. High Island was furthered scoured to the bedrock/clay layer. All beach sand was removed from the intertidal zone.

The loss of sediment also resulted in a recorded loss of all intertidal beach fauna. All the beaches experienced extreme loss/reworking of back dunes and beach face sediment. Based upon current levels of sea level rise, erosion, and subsidence, the resulting beach face and mean high tide after the hurricane demonstrated the average coastline migration to occur in nine years.

During the following nine months recovery between the study sites varied. All sites experienced some amount of recovery at least geologically. Surfside Beach and Jamaica Beach experienced moderate to heavy human interference during the nine months. Surfside Beach did not demonstrate recovery of macroinfauna during the nine months because of extensive use of the beach as a roadway for the first eight months. Recovery may have begun after this study was concluded. Jamaica Beach began to experience recovery before the winter senescence but growth was slow in the spring and evident only after this study during a separate community assessment study carried out in 2009. High Island's recovery could only increase because it was biologically wiped clean. The Sabine Pass site experienced the greatest natural recovery. This site experienced little to no human interference during recovery. It was remotely located and the hurricane damage to the road made it unusable. Abundance values and richness were not at the same levels in May as observed during previous summers, but population growth was observed.

Observations at this site along with the other study sites have led to believe that the resilience of this ecosystem is substantial. Ecological resilience is observed as the amount of change from one extreme to the other that the system can endure without undergoing a shift in community structure (Holling, 1973; Gunderson 2000). These disturbance prone beaches along the upper Texas coast are comprised of taxa that are capable of enduring, reestablishing, and thriving after habitat upheaval. These taxa have been known to be primary and secondary disturbance organisms (Dobbs and Vozarik, 1983; Allen and Moore, 1987; Jaramillo et al., 1987). The repeated disturbances could be the key to this community remaining in the early community development stage. Further long term research is needed to better understand the upper/more developed end of this ecological community, or even if it exists at all.

Allen and Moore (1987) found that macroinfauna could be used as an indicator of beach health. Examining the information collected during the baseline and recovery data sets showed that the haustoriid amphipods were a possible indicator taxa. They occurred in abundant quantities and exhibited defined seasonality and preference for beach sediments. Haustoriids exhibited defined zonation with a preference for the upper zones during the summer, then migrated to the swash and subtidal during the winter. Haustoriids also were affected by the reworking of sediment after the hurricane, affecting both abundance and zonation. Haustoriids at High Island during the recovery data set were low in abundance. Their presence was noted occurring only during the last four months of this study ranging from one to three individuals per transect. Beach sediment size was coarser at High Island than the other sites and also the slope and wave action was greater. Amphipods have been identified as a group with defined zonation and as a possible indicator species for beach stability (Croker, 1967; Donn and Croker, 1986; Allen and Moore, 1987). I suggest that more work needs to be conducted on this family to determine the actual species present, and the variation in zonation and seasonality, if more than one species is identified. Species determination will result in a better identification of an indicator species for beach health on the upper Texas coast. Species were not identified at this time because of the absence of key, guides or descriptions.

7.3 Conservation and the conflicting coastal exploitation

One of the most difficult responsibilities that modern day ecologists encounter is in the preservation of the biological world while people must live within that world (Adams, 1935; Roe and van Eeten 2001; Campbell et al., 2009; Weinstein, 2007). Roe and Van Eeten (2001, 2002) elegantly introduced this “dual mandate” as the conflict of conservation while increasing exploitation of natural resources. With 80% of the US population in coastal urban areas (Small and Cohen, 2004; Weinstein, 2007) keeping coastlines as sustainable environments is difficult. Immediate and continuing action will be needed to prevent irreversible alterations to the coastal environment (Palmer et al., 2004, Weinstein, 2007). Land use models with human dominated landscapes need to be changed lessening the impact of natural disturbance alterations and coastal migration while conserving flora and fauna endemic to the region. Cooperative and responsible action from scientists, land managers, and stakeholders will advance the success of this landscape and ecosystem (Roe and van Eeten, 2001). What will mitigation solve if unrestrained population growth and development continues along this ecosystem unchecked?

With the global climate undergoing change, sea level rise and increasing temperatures and tropical storms, coastal shorelines are undeniably affected. Inundation of low-lying coastlines and barrier islands will be expected as these temporary islands experience natural and man-induced coastal retreat. Although seemingly desolate, sandy beaches are important in providing a feeding ground and nesting area for migratory and residential birds as well as nursery for coastal and pelagic fish (Leber, 1982; Peterson et al., 2006; Schlacher et al., 2007). It is important to begin modifying our behavior and action along the shores to prevent this environment from undergoing a change to an alternative ecological state which could be devastating to local economies (Folke et al., 2004; Hughes et al., 2005; Biggs et al., 2009). It is my hope that this research will provide understanding of this fragile coastline in an effort to conserve and provide better management. Continued exploitation of the coastal environment could lead to barren unstable rocks and beaches.

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APPENDIX A

TEXAS HURRICANE HISTORY

Table A-1. List of Texas Hurricanes (circa 1527-2008)

Year	Date	Name	Landfall	Category	Highest Cat.	mph	TX Deaths, US
1527	Nov.		Galveston area?				200
1553			Padre area				1700
1766	Sept. 4		Galveston Bay				
1791			Lower coast				50000 cattle
1818	Sept. 12		Galveston Is.				
1829	Sept 10		Rio Grande				
1831	Aug 18		Rio Grande				
1834	Sept.		S. Texas				
1835	Aug.	Antigua H.	Rio Grande				
1837	Oct 5	Racer's Storm	s. Brownsville, up	Lg			Unk #
1838			Lower coast				
1939	Nov 5		Galveston				
1844	Aug 6		Rio Grande				70
1848	Oct. 17		Lower coast				
1854	Sept 19		Matagorda				4
1867	Oct 3		SW of Galveston	Lg			
1869	Aug 16		Refugio				
1871	Jun 2		TX coast				
1871	Jun 9		E. TX				1
1874	July		Indianola				
1875	Sept 16		Indianola				175
1877	Sept 15		Coast			60?	
1879	Aug 22		Orange				
1880	Aug 13		Matamoros, MX				5
1880	Oct 12		Brownsville				Unk #
1885	Sept 17		Brownsville				
1886	Aug 19		Indianola				Town
1886	Oct 12		Sabine				150
1887	Sept 21		Brownsville			78	
1888	June 16		NE. TX				
1888	July 5		Galveston				
Year	Date	Name	Landfall	Category	Highest Cat.	mph	TX Deaths, US
1891	July 13		Sabine Pass				
1897	Sept 12		Port Arthur				10, 29
1900	Sept 8		Galveston				6-12000
1902	June 27		Port Lavaca	min		65?	
1909	July 21		Velasco				41
1910	Sept 14		S. Padre Is			120	
1912	Oct 16		Brownsville	TS		55	
1913	June 27		Corpus Christi				

Year	Date	Name	Landfall	Category	Highest Cat.	mph	TX Deaths, US
1915	Aug 16		Galveston			>62	275
1916	Aug 18		Corpus Christi			90	20
1919	Sept 14		n. Corpus Christi			110	284, 600
1921	June 22		Corpus Christi			68	
1929	June 28		Pt. O'Conner			90?	3
1932	Aug 13		n. Freeport			100	40
1933	Aug 4		s. Brownsville			72	
1933	Sept 4		n. Brownville			80	40
1934	July 25		Rockport			54	19
1936	June 27		Port Aransas			80	
1941	Sept 23		n. Matagorda			83?	4
1942	Aug 30		Matagorda			>72	8
1943	July 27		n. Galveston			132	19
1945	Aug 26		Matagorda			135	3
1947	Aug 24		Galveston			72	1
1949	Oct 3		Freeport			135	2
1954	June 26	Alice	Brownsville	1		80	0, 38
1955	Sept 5	Gladys	s. Brownsville	1		90	Unk #
1957	Jun 27	Audrey	Sabine	4		85	9, 390
1959	July 24	Debra	Freeport	1		85	0
1960	June 23	unnamed	Padre Island			60	12, 15
1961	Sept 14	Carla	Port Lavaca	4	5	175	34, 46
1963	Sept 17	Cindy	High Island	1		75	3
1967	Sept 18	Beulah	N Brownsville	3	5, 160	136	13, 58
1970	Aug 3	Celia	Corpus Christi	3		125	11
1971	Sept 9	Fern	Coastal Bend	1		>100	2
1971	Sept 14	Edith	High Island	2	5, 160	105	0, 37
1978	July 30	Amelia	Padre Island	TS		50	30
1980	Aug 9	Allen	Corpus Christi	3	5, 190	138	3, 236
1983	Aug 15	Alicia	Galveston	3		102	18
1986	Jun 26	Bonnie	High Island	2		97	0
Year	Date	Name	Landfall	Category	Highest Cat.	mph	TX Deaths, US
1988	Sept 16	Gilbert	Brownsville	3	5	120	1
1999	Aug 22	Bret	Padre Is	3	4, 145	115	4, 7
2003	Jul 15	Claudette	Pt. O'Conner	1		90	1
2005	Sept 24	Rita	Sabine	3	5, 180	115	113
2007	Sept 13	Humberto	Sabine	1		90	0
2008	Sept 13	Ike	Galveston	2	4, 145	110	48, 195

Lg = noted as a large storm in records
TS = tropical storm
? = nearby town record
.> = town record more than 30 miles away

Table A-2. 50 years of Texas Storms

1960 – 1 storm, 1 hurricane	1986 – 1 storm, 1 hurricane
1961 – 1 storm, 1 hurricane	1987 – 1 storm
1962 – 0 storms	1988 – 0 storms
1963 – 1 storm, 1 hurricane	1989 – 3 storms, 2 hurricanes
1964 – 1 storm	1990 – 0 storms
1965 – 0 storms	1991 – 0 storms
1966 – 0 storms	1992 – 0 storms
1967 – 1 storm, 1 hurricane	1993 – 1 storm
1968 – 1 storm	1994 – 0 storms
1969 – 0 storms	1995 – 1 storm
1970 – 2 storms, 1 hurricane	1996 – 0 storms
1971 – 1 storm	1997 – 0 storms
1972 – 0 storms	1998 – 2 storms
1973 – 1 storm	1999 – 1 storm, 1 hurricane
1974 – 0 storms	2000 – 0 storms
1975 – 0 storms	2001 – 1 storm
1976 – 0 storms	2002 – 2 storms
1977 – 0 storms	2003 – 2 storms, 1 hurricane
1978 – 1 storm	2004 – 0 storms
1979 – 2 storms	2005 – 1 storm, 1 hurricane
1980 – 2 storms, 1 hurricane	2006 – 0 storms
1981 – 0 storms	2007 – 2 storms, 1 hurricane
1982 – 1 storm	2008 – 3 storms, 2 hurricanes
1983 – 1 storm, 1 hurricane	2009 – 0 storms
1984 – 0 storms	2010 – 1 hurricane
1985 – 0 storms	

Past 50 years = 38 storms, 16 hurricanes
Rate = 0.76 storms, 0.32 hurricanes

Sources used to compile data for hurricane list:
NWS – National Hurricane Center
Khou.com
TX almanac
Wikipedia

APPENDIX B

SUPPLEMENTAL BEACH MORPHODYNAMIC DATA

Table B-1. Monthly slope and beach width data from each study site along the upper Texas coast. *= measurement not taken

a. Sabine Pass

Dates	Slope (degree)	Beach width (m)
2007 July	1.44	*
2007 Aug	1.50	*
2007 Sep(1)	*	50.00
2007 Sep(2)	1.69	53.50
2007 Oct	1.91	63.05
2007 Nov	1.79	36.36
2007 Dec	1.83	38.95
2008 Jan	*	*
2008 Feb	1.67	58.50
2008 Mar	1.94	32.35
2008 Apr	1.97	25.50
2008 May	1.95	40.39
2008 Jun	2.20	33.80
2008 Jul	2.30	35.50
2008 Aug	1.82	34.50
2008 Sep	1.46	29.70
2008 Oct	1.75	25.20
2008 Nov	1.10	107.00
2008 Dec	1.28	72.18
2009 Jan	1.81	47.14
2009 Feb	*	*
2009 Mar	1.58	43.10
2009 Apr	1.66	36.90
2009 May	1.39	34.14

b. High Island

Dates	Slope (degree)	Beach width (m)
2007 July	2.57	*
2007 Aug	2.59	*
2007 Sep(1)	2.52	44.20
2007 Sep(2)	2.38	23.00
2007 Oct	2.48	42.20
2007 Nov	2.84	27.00
2007 Dec	2.74	30.35
2008 Jan	2.69	27.50
2008 Feb	2.86	31.85
2008 Mar	2.71	26.00
2008 Apr	2.49	18.40
2008 May	2.20	25.17
2008 Jun	3.19	24.60
2008 Jul	3.26	21.80
2008 Aug	3.04	26.80
2008 Sep	1.18	16.84
2008 Oct	1.38	*
2008 Nov	1.32	33.70
2008 Dec	0.75	8.99
2009 Jan	2.00	20.26
2009 Feb	*	*
2009 Mar	1.99	13.50
2009 Apr	1.63	7.85
2009 May	2.01	9.09

c. Jamaica Beach

Dates	Slope (degree)	Beach width (m)
2007 July	1.61	*
2007 Aug	1.85	45.50
2007 Sep(1)	1.73	49.59
2007 Sep(2)	1.95	38.80
2007 Oct	2.54	50.30
2007 Nov	2.00	35.75
2007 Dec	2.42	41.70
2008 Jan	3.27	40.00
2008 Feb	2.04	39.60
2008 Mar	1.87	37.90
2008 Apr	2.84	31.30
2008 May	2.14	28.30
2008 Jun	2.37	32.78
2008 Jul	2.37	36.10
2008 Aug	2.45	37.70
2008 Sep	1.63	12.50
2008 Oct	1.80	12.50
2008 Nov	2.27	28.40
2008 Dec	0.85	71.67
2009 Jan	0.96	62.00
2009 Feb	1.15	30.50
2009 Mar	1.16	35.10
2009 Apr	1.42	24.44
2009 May	1.51	28.30

d. Surfside Beach

Dates	Slope (degree)	Beach width (m)
2007 July	1.24	*
2007 Aug	1.29	65.70
2007 Sep(1)	1.34	64.08
2007 Sep(2)	1.39	57.90
2007 Oct	1.33	70.87
2007 Nov	1.63	42.76
2007 Dec	1.64	49.32
2008 Jan	1.90	41.94
2008 Feb	1.93	43.30
2008 Mar	1.57	36.30
2008 Apr	1.61	26.50
2008 May	1.83	32.00
2008 Jun	1.84	42.40
2008 Jul	1.68	42.40
2008 Aug	1.63	46.30
2008 Sep	0.93	66.00
2008 Oct	0.98	50.40
2008 Nov	0.77	124.35
2008 Dec	0.87	77.80
2009 Jan	1.10	79.90
2009 Feb	0.89	64.33
2009 Mar	0.90	65.90
2009 Apr	0.83	58.20
2009 May	0.63	54.00

Table B-2. Beach morphodynamic data and indices for each study site along the upper Texas coast. *= measurement not taken. # = measurement calculation missing variable.

a. Sabine Pass

Dates	Grain size (µm)	Water temp (°F)	Salinity (ppt)	Wave height (cm)	Sandfall velocity (cm/sec)	Wave period (sec)	Tide range (m)	Slope (°)	Deans parameter	RTR	BI
Jul-07	172	33	23	38	1.69	3.38	1.20	1.50	6.64	3.17	2.49
Dec-07	178	21	28	512	1.78	8.01	1.56	1.83	35.94	0.30	2.71
Jul-08	304	32	29	35	4.25	3.91	1.21	2.30	2.11	3.45	2.93
Sep-08	695	27	23	81	10.78	3.90	3.48	1.46	1.93	4.29	3.55
Dec-08	133	10	28	129	1.13	3.99	1.60	1.28	28.65	1.24	2.44

b. High Island

Dates	Grain size (µm)	Water temp (°F)	Salinity (ppt)	Wave height (cm)	Sandfall velocity (cm/sec)	Wave period (sec)	Tide range (m)	Slope (°)	Deans parameter	RTR	BI
Jul-07	334	31	24	38	4.90	3.38	1.20	2.59	2.29	3.17	3.02
Dec-07	757	19	27	512	11.04	8.01	1.56	2.74	5.79	0.30	3.51
Jul-08	391	33	30	35	5.81	3.91	1.21	3.26	1.54	3.45	3.19
Sep-08	Clay	25	25	33	0.00	3.30	3.48	1.18	#	10.53	#
Dec-08	368	13	27	129	4.93	3.99	1.60	0.76	6.56	1.24	2.65

c. Jamaica Beach

Dates	Grain size (µm)	Water temp (°F)	Salinity (ppt)	Wave height (cm)	Sandfall velocity (cm/sec)	Wave period (sec)	Tide range (m)	Slope (°)	Deans parameter	RTR	BI
Jul-07	121	31	28	61	1.19	3.67	1.20	1.85	13.94	1.97	2.43
Dec-07	145	19	19	107	1.33	4.76	1.56	2.42	16.87	1.46	2.74
Jul-08	128	31	32	29	1.31	3.54	1.21	2.37	6.27	4.16	2.56
Sep-08	152	27	26	30	1.74	6.67	3.48	1.63	2.58	11.58	2.93
Dec-08	160	14	28	33	1.52	3.30	1.60	0.85	6.59	4.86	2.34
Jun-09	130	29	31	41	1.34	3.13	1.15	1.51	9.77	2.80	2.35

d. Surfside Beach

Dates	Grain size (µm)	Water temp (°F)	Salinity (ppt)	Wave height (cm)	Sandfall velocity (cm/sec)	Wave period (sec)	Tide range (m)	Slope (°)	Deans parameter	RTR	BI
Jul-07	121	32	28	61	1.19	3.67	1.12	1.29	13.94	1.84	2.24
Dec-07	147	19	27	107	1.33	4.76	1.37	1.64	16.89	1.28	2.52
Jul-08	129	32	30	29	1.32	3.54	1.15	1.68	6.19	3.98	2.40
Sep-08	156	26	23	81	1.81	3.90	2.29	0.93	11.46	2.82	2.52
Dec-08	150	15	29	41	1.37	3.13	1.56	0.87	9.53	3.80	2.31

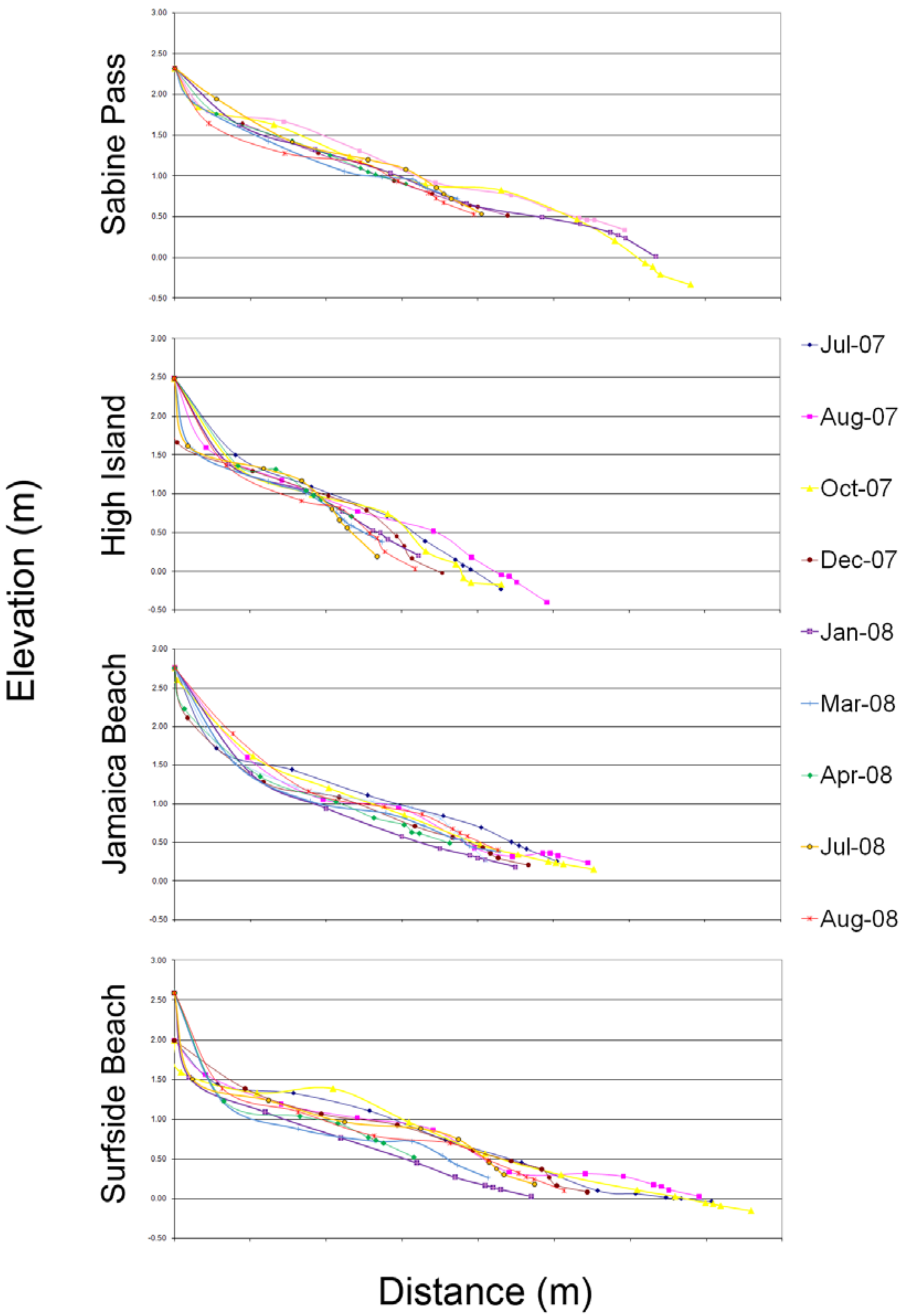

Fig. B-1. Beach elevation profile from each study site along the upper Texas coast from July 2007 through August 2008.

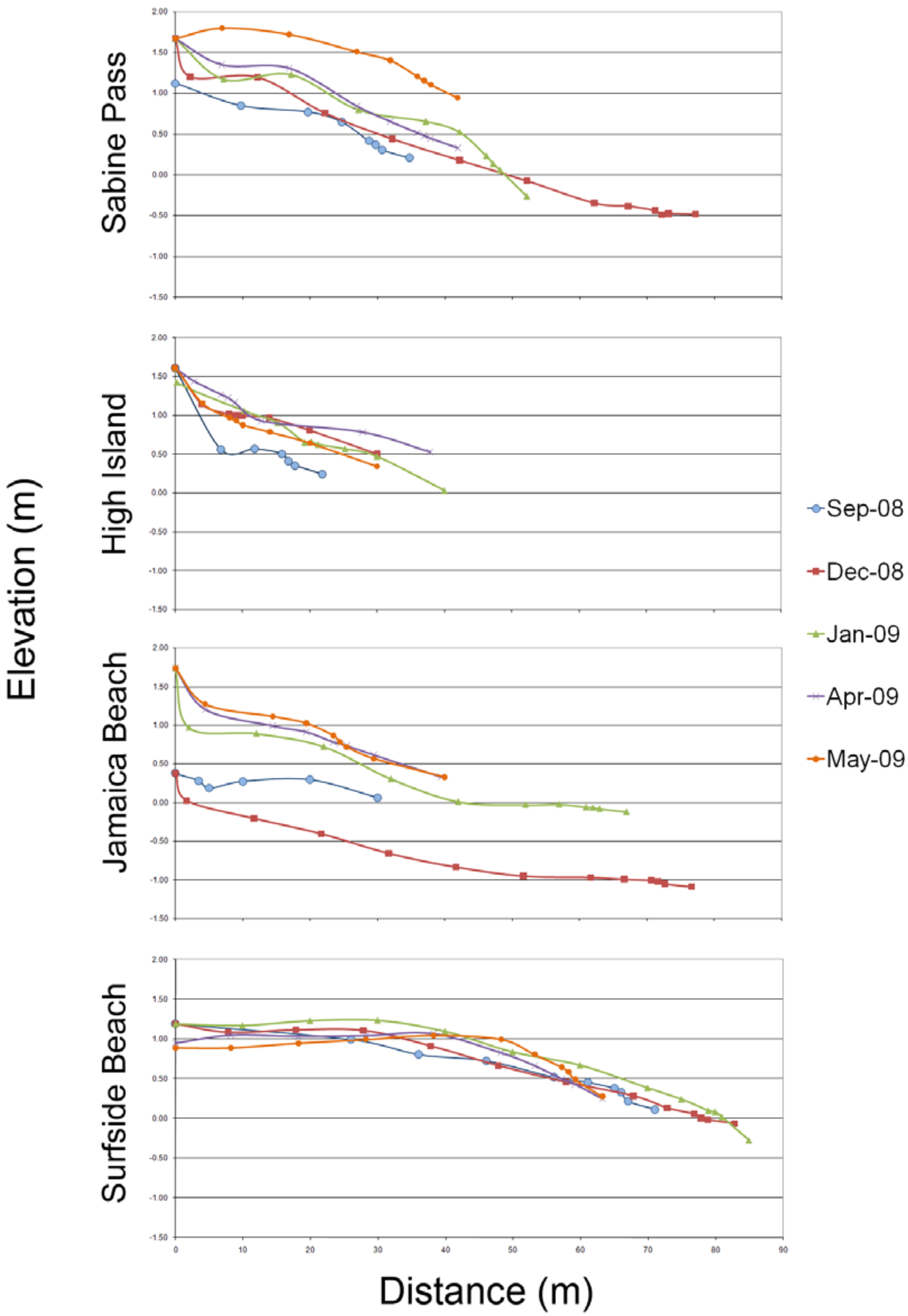

Fig. B-2. Beach elevation profile from each study site along the upper Texas coast from September 2008 through May 2009.

APPENDIX C

UPPER TEXAS COAST INTERTIDAL SPECIES LIST

List of invertebrate macrofauna found in cores during the course of this study along the upper Texas coast intertidal zone. Species were identified to the lowest taxonomic level possible. Resources used for identification follow the list.

Benthic taxa

Polychaeta
- *Scolelepis squamata* O. F. Mueller, 1806
- *Lumbrineris* sp. Blainville, 1828
- Spionidae Grube, 1850
- *Eunice antennata* Savigny, 1820
- *Nephtys* sp. Cuvier, 1817
- *Platynereis dumerilii* Audouin and Milne-Edwards, 1833
- *Scoloplos fragilis* *Scoloplos* Blainville, 1828
- *Magelona* sp. Mueller, 1858
- *Microphthalmus fragilis* Bobretzky, 1870
- *Dorvillea* sp. Parfitt, 1866

Amphipoda
- *Orchestia* sp. Leach, 1814
- Haustoriidae Stebbing, 1906
- Corophiidae Leach, 1814

Isopoda
- *Ancinus depressus* Say, 1818
- *Janira minuta* *Janira* Leach, 1814

Decapoda
- *Emerita portoricensis* Schmitt, 1935
- Juv. *Emerita* sp. Scopoli, 1777
- *Lepidopa benedicti* Schmitt, 1935
- *Austinixa beherae* Manning and Felder, 1989
- *Isocheles wurdemanni* Stimpson, 1862
- *Callichirus islagrande* Schmitt, 1935

Bivalvia
- juv. *Donax* sp. Linnaeus, 1758
- *Donax texasianus* Philippi, 1847
- *Donax variablis* Say, 1822
- juv. *Petricolaria* sp. Stoliczka, 1870

Petricolaria pholadiformis Lamarck, 1818
juv. Arcidae Lamarck, 1809
juv. Oliva Bruguiere, 1789
juv. Bivalvia Linnaeus, 1758
Barbatia cancellaria (juvenile) Lamarck, 1819

Cumacea
Alymyracuma sp.

Pelagic taxa

Decapoda
Latreutes fucorum J. C. Fabricius, 1798
Callinectes sapidus M. J. Rathbun, 1896
Arenaeus cribrarius Lamarck, 1818
Crab megalopa Latreille, 1802

Other
Sagitta sp. Quoy and Gaimard, 1827
Copepod Milne-Edwards, 1840
Zoea Latreille, 1802
Mysida Haworth, 1825
Ophiuroidea Gray, 1840

Terrestrial taxa
Bledius sp. Leach, 1819
Caprella sp. Lamarck, 1801
Araneae – spider
Acari – mite
Diptera – fly
Diptera – fly larva
Formicidae – ant
Oligochaeta

Identification resources:

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APPENDIX D

SUPPLEMENTAL BIOLOGICAL DATA AND RAW DATA

Table D-1 Most common and abundant six taxa with total transect data of abundance (N), richness (S), Shannon's Diversity (H), and Evenness (E). Study sites along the upper Texas coast included Surfside Beach (SS), Jamaica Beach (JB), High Island (HI), and Sabine Pass (SP).

Date	Site	Tran sect	*Scolel epis*	*Lumbri neris*	Haustor iidae	*Ancinus*	*Emerita*	*Donax*	N	S	H	E
July 2007	SS	a	50	0	248	0	0	3	301	3	0.50	0.46
July 2007	SS	b	25	2	109	0	0	6	142	4	0.70	0.51
July 2007	JB	a	72	0	66	0	0	22	161	3	1.00	0.91
July 2007	JB	b	140	0	115	0	0	23	278	3	0.92	0.83
July 2007	HI	a	1	0	0	0	0	0	1	1	0.00	0.00
July 2007	HI	b	4	0	0	0	0	2	6	2	0.64	0.92
July 2007	SP	b	36	0	239	0	0	4	281	4	0.50	0.36
August 2007	SS	a	3	0	4	0	4	72	85	5	0.59	0.37
August 2007	SS	b	7	0	13	0	6	80	108	6	0.90	0.50
August 2007	JB	a	457	7	19	0	0	19	503	5	0.41	0.25
August 2007	JB	b	466	1	7	0	9	91	574	5	0.59	0.37
August 2007	HI	a	10	2	1	0	2	102	120	6	0.59	0.33
August 2007	HI	b	7	0	0	1	1	32	80	5	1.04	0.65
August 2007	SP	a	2	2	7	12	1	10	34	6	1.49	0.83
August 2007	SP	b	2	1	13	0	0	22	40	6	1.12	0.63
September 2007	SS	a	0	0	0	0	0	0	0	0	N/A	N/A
September 2007	SS	b	9	2	14	0	0	14	41	6	1.40	0.78
September 2007	JB	a	138	0	3	0	0	15	159	5	0.51	0.32
September 2007	JB	b	80	2	5	0	0	38	128	5	0.93	0.58
September 2007	HI	a	1	4	0	17	1	9	37	7	1.47	0.76
September 2007	HI	b	1	0	0	2	1	3	16	7	1.63	0.84
September 2007	SP	a	2	0	0	0	0	7	9	2	0.53	0.76
September 2007	SP	b	5	0	0	1	0	15	22	4	0.88	0.63
September2 2007	SS	a	0	0	15	3	2	51	71	4	0.80	0.58
September2 2007	SS	b	2	4	4	2	1	34	47	6	1.00	0.56
September2 2007	JB	a	349	1	2	0	3	51	407	6	0.48	0.27
September2 2007	JB	b	250	0	2	0	2	39	293	4	0.47	0.34
September2 2007	HI	a	75	0	0	0	0	7	82	2	0.29	0.42
September2 2007	HI	b	89	0	0	0	0	0	89	1	0.00	0.00
September2 2007	SP	a	0	3	0	0	0	1	4	2	0.56	0.81
September2 2007	SP	b	0	1	1	0	0	4	7	4	1.15	0.83
October 2007	SS	a	1	2	18	0	0	9	35	6	1.31	0.73
October 2007	SS	b	0	1	25	0	0	4	32	5	0.78	0.48
October 2007	JB	a	1	2	10	0	0	7	24	6	1.48	0.82
October 2007	JB	b	0	0	12	0	0	7	20	3	0.82	0.75
October 2007	HI	a	0	0	0	0	0	2	2	1	0.00	0.00
October 2007	HI	b	0	0	0	2	0	6	9	3	0.85	0.77
October 2007	SP	a	13	0	22	45	0	0	80	3	0.97	0.89
October 2007	SP	b	31	0	18	27	0	0	82	5	1.29	0.80
November 2007	SS	a	1	0	19	0	1	4	25	4	0.76	0.55
November 2007	SS	b	16	0	57	0	0	0	73	2	0.53	0.76
November 2007	JB	a	88	0	23	0	0	5	116	3	0.67	0.61
November 2007	JB	b	105	1	99	0	0	9	216	5	0.91	0.56
November 2007	HI	a	27	0	0	0	0	1	28	2	0.15	0.22
November 2007	HI	b	39	0	0	0	0	0	39	1	0.00	0.00
November 2007	SP	a	54	0	86	0	0	2	142	3	0.73	0.67
November 2007	SP	b	58	1	193	0	0	1	253	4	0.59	0.42
December 2007	SS	a	32	1	154	1	0	9	197	5	0.68	0.42
December 2007	SS	b	88	0	96	2	0	3	190	5	0.84	0.52
December 2007	JB	a	82	0	88	0	0	16	186	3	0.93	0.84
December 2007	JB	b	109	0	75	0	0	11	195	3	0.85	0.78

Date	Site	Tran sect	*Scolel epis*	*Lumbri neris*	Haustor iidae	*Ancinus*	*Emerita*	*Donax*	N	S	H	E
December 2007	HI	a	24	0	0	0	0	0	24	1	0.00	0.00
December 2007	HI	b	4	0	1	0	0	0	5	2	0.50	0.72
December 2007	SP	a	48	1	321	0	0	1	371	4	0.42	0.30
December 2007	SP	b	28	0	307	0	0	1	337	4	0.33	0.24
January 2008	SS	b	111	0	73	0	0	1	185	3	0.70	0.64
January 2008	JB	b	90	0	52	0	0	3	145	3	0.74	0.68
January 2008	HI	b	21	0	0	0	0	0	21	1	0.00	0.00
February 2008	SS	a	9	0	113	0	0	3	128	4	0.47	0.34
February 2008	SS	b	19	0	81	0	1	0	106	5	0.73	0.45
February 2008	JB	a	6	1	123	0	0	21	151	4	0.60	0.43
February 2008	JB	b	23	1	262	0	0	6	292	4	0.40	0.29
February 2008	HI	a	35	0	0	0	0	0	35	1	0.00	0.00
February 2008	HI	b	37	0	0	0	0	0	37	1	0.00	0.00
February 2008	SP	a	0	0	41	2	0	4	47	3	0.46	0.42
February 2008	SP	b	0	0	24	3	0	3	30	3	0.64	0.58
March 2008	SS	a	11	0	231	1	0	3	247	5	0.30	0.19
March 2008	SS	b	12	0	170	1	0	3	187	5	0.39	0.24
March 2008	JB	a	10	1	317	0	0	6	334	4	0.24	0.18
March 2008	JB	b	13	0	278	0	0	24	317	5	0.48	0.30
March 2008	HI	a	17	0	0	0	0	0	18	2	0.21	0.31
March 2008	HI	b	58	0	0	0	0	0	58	1	0.00	0.00
March 2008	SP	a	16	0	692	2	0	0	710	3	0.13	0.12
March 2008	SP	b	19	0	500	4	0	2	531	5	0.28	0.18
April 2008	SS	a	122	0	81	0	0	0	203	2	0.67	0.97
April 2008	SS	b	123	0	139	0	0	0	266	3	0.76	0.69
April 2008	JB	a	59	1	324	7	0	50	446	7	0.88	0.45
April 2008	JB	b	56	1	294	5	0	54	419	7	0.94	0.48
April 2008	HI	a	104	0	0	0	0	0	105	2	0.05	0.08
April 2008	HI	b	26	0	0	0	0	0	26	1	0.00	0.00
April 2008	SP	a	51	0	715	2	0	0	770	4	0.28	0.20
April 2008	SP	b	53	0	668	1	0	0	722	3	0.27	0.25
May 2008	SS	a	48	0	223	1	0	5	277	4	0.57	0.41
May 2008	SS	b	58	1	245	0	0	8	312	4	0.61	0.44
May 2008	JB	a	101	0	673	0	0	6	781	4	0.44	0.32
May 2008	JB	b	82	0	220	3	0	8	314	5	0.76	0.47
May 2008	HI	a	31	0	0	0	0	0	32	1	0.00	0.00
May 2008	HI	b	5	0	0	0	0	0	5	1	0.00	0.00
May 2008	SP	a	10	3	435	1	0	1	452	6	0.19	0.11
May 2008	SP	b	11	1	550	0	0	11	574	5	0.21	0.13
June 2008	SS	a	366	10	163	0	11	0	551	5	0.79	0.49
June 2008	SS	b	480	4	138	0	2	2	628	6	0.63	0.35
June 2008	JB	a	414	1	369	0	4	0	788	4	0.73	0.53
June 2008	JB	b	492	2	472	0	0	1	967	4	0.71	0.51
June 2008	HI	a	32	1	0	8	3	1	46	6	0.98	0.55
June 2008	HI	b	29	2	0	0	3	0	34	3	0.52	0.47
June 2008	SP	a	61	2	575	0	0	1	639	4	0.35	0.25
June 2008	SP	b	30	0	580	0	0	0	610	2	0.20	0.28
July 2008	SS	a	705	7	61	1	42	27	844	7	0.66	0.34
July 2008	SS	b	639	3	168	0	12	38	863	6	0.78	0.43
July 2008	JB	a	345	0	484	0	12	5	846	4	0.78	0.56
July 2008	JB	b	396	1	780	0	25	26	1228	5	0.82	0.51
July 2008	HI	a	58	2	0	0	0	0	60	2	0.15	0.21
July 2008	HI	b	54	0	0	0	1	0	55	2	0.09	0.13
July 2008	SP	a	105	0	226	2	3	5	341	5	0.77	0.48
July 2008	SP	b	113	0	157	2	1	4	277	5	0.80	0.50
August 2008	SS	a	358	1	129	0	15	0	613	5	1.05	0.65
August 2008	SS	b	381	10	95	1	7	0	568	6	0.97	0.54
August 2008	JB	a	329	1	51	0	17	0	442	5	0.84	0.52
August 2008	JB	b	322	1	122	1	4	0	511	6	0.95	0.53
August 2008	HI	a	49	0	0	0	1	0	50	2	0.10	0.14
August 2008	HI	b	66	0	0	0	0	0	66	1	0.00	0.00
August 2008	SP	b	204	0	313	1	3	0	522	5	0.73	0.45
September 2008	SS	a	30	3	6	0	0	11	50	4	1.06	0.77
September 2008	SS	b	28	2	1	0	0	15	46	4	0.89	0.64
September 2008	JB	a	12	0	70	0	0	1	84	4	0.54	0.39
September 2008	JB	b	16	0	127	0	0	1	144	3	0.39	0.35
September 2008	HI	a	0	0	0	0	0	0	0	0	N/A	N/A
September 2008	HI	b	0	0	0	0	0	0	0	0	N/A	N/A
September 2008	SP	b	1	0	12	0	1	1	15	4	0.72	0.52

Date	Site	Tran sect	*Scolel epis*	*Lumbri neris*	Haustor iidae	*Ancinus*	*Emerita*	*Donax*	N	S	H	E
October 2008	SS	a	111	0	51	0	0	1	163	3	0.66	0.60
October 2008	SS	b	92	0	88	2	1	3	186	5	0.85	0.53
October 2008	JB	a	6	0	29	0	2	1	38	4	0.75	0.54
October 2008	JB	b	13	2	16	1	1	0	33	5	1.10	0.68
October 2008	HI	a	3	0	0	0	0	0	3	1	0.00	0.00
October 2008	HI	b	0	0	0	0	0	0	0	0	N/A	N/A
October 2008	SP	a	16	0	8	0	1	1	26	4	0.91	0.66
October 2008	SP	b	6	0	5	0	0	1	12	3	0.92	0.84
November 2008	SS	a	0	1	15	0	0	5	25	6	1.22	0.68
November 2008	SS	b	0	0	16	3	0	1	23	5	1.00	0.62
November 2008	JB	a	1	0	18	1	1	3	31	7	1.35	0.69
November 2008	JB	b	1	1	25	1	0	1	31	7	0.84	0.43
November 2008	HI	a	0	1	0	1	0	3	42	4	0.48	0.34
November 2008	HI	b	0	0	0	0	0	0	32	1	0.00	0.00
November 2008	SP	a	3	0	67	23	0	1	103	6	1.03	0.58
November 2008	SP	b	13	0	51	27	0	1	124	8	1.58	0.76
December 2008	SS	a	1	1	10	0	0	2	15	5	1.08	0.67
December 2008	SS	b	0	0	9	0	0	0	9	1	0.00	0.00
December 2008	JB	a	0	1	13	0	0	2	21	6	1.23	0.69
December 2008	JB	b	0	2	13	0	0	1	22	6	1.30	0.73
December 2008	HI	a	5	0	0	0	0	0	5	1	0.00	0.00
December 2008	HI	b	8	0	0	0	0	0	8	1	0.00	0.00
December 2008	SP	a	0	0	39	0	0	2	42	3	0.30	0.28
December 2008	SP	b	0	0	40	0	0	2	46	3	0.47	0.43
January 2009	SS	a	2	0	11	0	1	1	19	6	1.31	0.73
January 2009	SS	b	0	0	22	0	1	6	38	5	1.13	0.70
January 2009	JB	a	0	2	23	0	0	4	31	4	0.84	0.61
January 2009	JB	b	0	3	28	0	0	3	37	5	0.87	0.54
January 2009	HI	a	0	0	0	0	0	0	0	0	N/A	N/A
January 2009	HI	b	0	0	0	0	0	0	0	0	N/A	N/A
January 2009	SP	a	6	0	15	0	0	0	21	2	0.60	0.86
January 2009	SP	b	10	0	67	0	0	0	77	2	0.39	0.56
February 2009	SS	a	2	0	22	0	0	0	24	2	0.29	0.41
February 2009	SS	b	0	0	17	1	1	0	19	3	0.41	0.37
February 2009	JB	a	1	0	13	0	0	0	14	2	0.26	0.37
February 2009	JB	b	1	0	4	0	1	0	6	3	0.87	0.79
February 2009	HI	a	2	0	0	0	0	0	2	1	0.00	0.00
February 2009	HI	b	1	0	1	0	0	0	2	2	0.69	1.00
February 2009	SP	a	7	1	137	0	0	0	147	4	0.30	0.22
February 2009	SP	b	15	0	168	0	0	1	189	4	0.43	0.31
March 2009	SS	a	0	2	5	0	0	0	7	2	0.60	0.86
March 2009	SS	b	0	0	8	0	0	0	8	1	0.00	0.00
March 2009	JB	a	1	0	19	0	0	1	21	3	0.38	0.35
March 2009	JB	b	0	0	24	0	0	0	25	2	0.17	0.24
March 2009	HI	a	1	0	0	0	0	0	1	1	0.00	0.00
March 2009	HI	b	0	0	1	0	0	0	1	1	0.00	0.00
March 2009	SP	a	4	0	18	0	0	0	22	2	0.47	0.68
March 2009	SP	b	6	0	80	0	0	0	88	3	0.36	0.32
April 2009	SS	a	0	0	0	0	0	0	0	0	N/A	N/A
April 2009	SS	b	0	0	1	0	0	0	1	1	0.00	0.00
April 2009	JB	a	1	0	32	0	1	0	35	4	0.39	0.28
April 2009	JB	b	0	0	15	0	0	1	16	2	0.23	0.34
April 2009	HI	a	10	0	2	0	0	4	16	3	0.90	0.82
April 2009	HI	b	0	0	1	0	0	0	1	1	0.00	0.00
April 2009	SP	a	34	0	174	0	0	114	322	3	0.94	0.85
April 2009	SP	b	35	1	167	0	0	162	365	4	0.96	0.69
May 2009	SS	a	4	0	1	0	0	1	6	3	0.87	0.79
May 2009	SS	b	8	0	0	1	0	0	9	2	0.35	0.50
May 2009	JB	a	3	0	14	0	0	1	18	3	0.65	0.60
May 2009	JB	b	1	0	28	1	0	1	33	5	0.63	0.39
May 2009	HI	a	8	1	1	0	0	0	10	3	0.64	0.58
May 2009	HI	b	3	3	2	0	0	1	9	4	1.31	0.95
May 2009	SP	a	29	0	516	0	0	31	576	3	0.41	0.37
May 2009	SP	b	17	0	363	0	0	20	400	3	0.37	0.34
June 2009	JB	a	17	0	60	1	3	2	85	6	0.91	0.51
June 2009	JB	b	44	0	66	2	1	3	116	5	0.89	0.56

Table D-2. Biological data from August and September 2008 before and after Hurricane Ike with the six most common and abundant taxa.

Date	Site	Station	Transect	Scolelepis	Lumbrineris	Haustoriidae	Ancinus	Emerita	Callichirus	Donax	N	S	H'	E
August	SS	-5	a	10		6		5		9	30	4	1.35	0.97
August	SS	-5	b	6	1	4				11	22	4	1.15	0.83
August	SS	-1	a	24	1	2		5		36	68	5	1.06	0.66
August	SS	-1	b	16	4	1		5		29	55	5	1.18	0.73
August	SS	0	a	31		1		4		38	74	4	0.92	0.67
August	SS	0	b	17	2		1	1		9	30	5	1.09	0.68
August	SS	1	a	77				1		24	102	3	0.60	0.54
August	SS	1	b	103	3	2		1		25	134	5	0.70	0.43
August	SS	5	a	185		74				3	262	3	0.65	0.60
August	SS	5	b	234		88					322	2	0.59	0.85
August	SS	10	a	31		46					77	2	0.67	0.97
August	SS	10	b	5							5	1	0.00	0.00
August	JB	-5	a	41	1					15	57	3	0.66	0.60
August	JB	-5	b	29	1		1			13	44	4	0.81	0.58
August	JB	-1	a	118		2		4		19	143	4	0.59	0.42
August	JB	-1	b	123		2		1		28	154	4	0.58	0.42
August	JB	0	a	104		2		13		8	127	4	0.64	0.46
August	JB	0	b	129				3		17	149	3	0.45	0.41
August	JB	1	a	60		24				2	86	3	0.69	0.63
August	JB	1	b	38		8				1	47	3	0.56	0.51
August	JB	5	a	2		21					23	2	0.30	0.43
August	JB	5	b	3		111				2	116	3	0.21	0.19
August	JB	10	a	4		1					5	2	0.50	0.72
August	JB	10	b			1					1	1	0.00	0.00
August	HI	-5	a								0	0	n/a	n/a
August	HI	-5	b								0	0	n/a	n/a
August	HI	-1	a	5							5	1	0.00	0.00
August	HI	-1	b	8							8	1	0.00	0.00
August	HI	0	a	15				1			16	2	0.23	0.34
August	HI	0	b	14							14	1	0.00	0.00
August	HI	1	a	29							29	1	0.00	0.00
August	HI	1	b	44							44	1	0.00	0.00
August	HI	5	a								0	0	n/a	n/a
August	HI	5	b								0	0	n/a	n/a
August	HI	10	a								0	0	n/a	n/a
August	HI	10	b								0	0	n/a	n/a
August	SP	-5	b	20							20	1	0.00	0.00
August	SP	-1	b	64		18					82	2	0.53	0.76
August	SP	0	b	41		25	1	3		1	71	5	0.94	0.58
August	SP	1	b	62		94					156	2	0.67	0.97
August	SP	5	b	17		176					193	2	0.30	0.43
August	SP	10	b								0	0	n/a	n/a
September	SS	-5	a			1				6	7	2	0.41	0.59
September	SS	-5	b		2						2	1	0.00	0.00
September	SS	-1	a		2	1					3	2	0.64	0.92
September	SS	-1	b			1				10	11	2	0.30	0.44
September	SS	0	a			1				2	3	2	0.64	0.92
September	SS	0	b							4	4	1	0.00	0.00
September	SS	1	a	1	1					1	3	3	1.10	1.00
September	SS	1	b	1						1	2	2	0.69	1.00
September	SS	5	a							2	2	1	0.00	0.00
September	SS	5	b								0	0	n/a	n/a
September	SS	10	a	29		3					32	2	0.31	0.45
September	SS	10	b	27							27	1	0.00	0.00
September	JB	-5	a	1		3			1		5	3	0.95	0.86
September	JB	-5	b								0	0	n/a	n/a
September	JB	-1	a	6		1					7	2	0.41	0.59
September	JB	-1	b	5		1					6	2	0.45	0.65
September	JB	0	a			4				1	5	2	0.50	0.72
September	JB	0	b	4		71				1	76	3	0.28	0.25
September	JB	1	a	5		10					15	2	0.64	0.92
September	JB	1	b	4		20					24	2	0.45	0.65
September	JB	5	a			44					44	1	0.00	0.00
September	JB	5	b			12					12	1	0.00	0.00
September	JB	10	a			8					8	1	0.00	0.00

Date	Site	Stati on	Tran sect	Scolel epis	Lumbr ineris	Haustor iidae	Anci nus	Eme rita	Calli chiru s	Don ax	N	S	H'	E
September	JB	10	b	3		23					26	2	0.36	0.52
September	HI	-5	a								0	0	n/a	n/a
September	HI	-5	b								0	0	n/a	n/a
September	HI	-1	a								0	0	n/a	n/a
September	HI	-1	b								0	0	n/a	n/a
September	HI	0	a								0	0	n/a	n/a
September	HI	0	b								0	0	n/a	n/a
September	HI	1	a								0	0	n/a	n/a
September	HI	1	b								0	0	n/a	n/a
September	HI	5	a								0	0	n/a	n/a
September	HI	5	b								0	0	n/a	n/a
September	HI	10	a								0	0	n/a	n/a
September	HI	10	b								0	0	n/a	n/a
September	SP	-5	b	1		5					6	2	0.45	0.65
September	SP	-1	b								0	0	n/a	n/a
September	SP	0	b							1	1	1	0.00	0.00
September	SP	1	b					1			1	1	0.00	0.00
September	SP	5	b			1					1	1	0.00	0.00
September	SP	10	b			6					6	1	0.00	0.00
Total				1796	18	925	3	48	1	319	3110	7	1.01	0.52

Table D-3. Three years of June biological data with total abundance (N) and richness (S). a) all data. b) data pooled over stations. c) data averaged.

June year	Station	transect	*Scolelepis*	*Lumbrineris*	Haustoriidae	Ancinus	*Emerita*	*Austinixa*	*Donax*	N	S
2007	-5	a	5	0	0	0	0	0	16	21	2
2007	-5	b	3	0	14	0	0	0	16	33	3
2007	-1	a	0	0	0	0	0	0	0	0	0
2007	-1	b	45	0	34	0	0	0	0	79	2
2007	0	a	62	0	64	0	0	0	1	127	3
2007	0	b	26	0	35	0	0	0	1	62	3
2007	1	a	0	0	0	0	0	0	0	0	0
2007	1	b	47	0	29	0	0	0	2	78	3
2007	5	a	5	0	2	0	0	0	5	13	4
2007	5	b	19	0	3	0	0	0	4	26	3
2007	10	a	0	0	0	0	0	0	0	0	0
2007	10	b	0	0	0	0	0	0	0	0	0
2008	-5	a	2	1	0	0	4	0	0	7	3
2008	-5	b	15	1	0	0	0	0	1	17	3
2008	-1	a	167	0	4	0	0	0	0	171	2
2008	-1	b	124	0	33	0	0	0	0	157	2
2008	0	a	155	0	49	0	0	0	0	204	2
2008	0	b	120	1	43	0	0	0	0	164	3
2008	1	a	84	0	241	0	0	0	0	325	2
2008	1	b	199	0	237	0	0	0	0	436	2
2008	5	a	6	0	75	0	0	0	0	81	2
2008	5	b	32	0	159	0	0	0	0	191	2
2008	10	a	0	0	0	0	0	0	0	0	0
2008	10	b	2	0	0	0	0	0	0	2	1
2009	-7	a	0	0	1	1	0	2	1	5	4
2009	-7	b	0	0	1	2	0	0	0	3	2
2009	-3	a	0	0	0	0	1	0	0	1	1
2009	-3	b	0	0	9	0	0	0	1	10	2
2009	0	a	0	0	6	0	2	0	1	9	3
2009	0	b	4	0	13	0	1	0	2	20	4
2009	3	a	16	0	52	0	0	0	0	68	2
2009	3	b	39	0	43	0	0	0	0	82	2
2009	10	a	1	0	1	0	0	0	0	2	2
2009	10	b	1	0	0	0	0	0	0	1	1

b.

June year	Transect	*Scolelepis*	*Lumbrineris*	Haustoriidae	*Ancinus*	*Emerita*	*Austinixa*	*Donax*	N	S
2007	a	72	0	66	0	0	0	22	161	4
2007	b	140	0	115	0	0	0	23	278	3

2008	a	414	1	369	0	4	0	0	788	4
2008	b	492	2	472	0	0	0	1	967	4
2009	a	17	0	60	1	3	2	2	85	6
2009	b	44	0	66	2	1	0	3	116	5

c.

June year	Transect	*Scolelepis*	*Lumbrineris*	Haustoriidae	*Ancinus*	*Emerita*	*Austinixa*	*Donax*	N	S
2007	avg	106	0	91	0	0	0	23	220	4
	sd	48.0833	0	34.648	0	0	0	0.7071	82.731	
2008	avg	453	2	421	0	2	0	1	878	5
	sd	55.1543	0.7071	72.832	0	2.8284	0	0.7071	126.57	
2009	avg	31	0	63	2	2	1	3	101	6
	sd	19.0919	0	4.2426	0.7071	1.4142	1.4142	0.7071	21.92	

Table D-4. Community analysis

Transect	Station	*Scolelepis*	*Lumbrineris*	*Scoloplos*	Haustoriidae	*Ancinus*	*Emerita*	*Lepidopa*	*Austinixa*	*Donax*	N	S
a	1	0	0	0	1	1	0	0	2	1	5	9
b	1	0	0	0	0	0	0	0	1	0	1	9
c	1	0	0	0	1	2	0	0	0	0	3	9
d	1	0	1	0	7	0	0	0	1	0	9	9
e	1	0	0	0	0	0	0	0	0	0	0	9
f	1	0	1	0	2	0	0	0	0	0	3	9
g	1	0	1	1	0	0	0	0	1	0	3	9
h	1	0	0	0	0	0	0	0	0	1	1	9
i	1	0	1	0	0	1	0	0	0	0	2	9
j	1	0	1	0	1	0	0	0	0	0	2	9
k	1	0	0	0	0	0	0	0	0	0	0	9
l	1	0	0	0	1	0	0	0	0	1	2	9
m	1	0	1	0	0	0	1	0	1	0	3	9
a	2	0	0	0	0	0	1	0	0	0	1	9
b	2	3	0	0	1	0	0	0	0	4	8	9
c	2	0	0	0	9	0	0	0	0	1	10	9
d	2	0	0	0	4	0	0	0	1	2	7	9
e	2	0	0	0	14	0	0	0	0	2	16	9
f	2	0	1	0	6	0	1	0	0	1	9	9
g	2	2	0	0	0	0	0	0	3	0	5	9
h	2	2	0	0	20	0	0	0	0	4	26	9
i	2	0	0	0	4	0	1	0	2	2	9	9
j	2	0	0	0	3	0	0	0	0	3	6	9
k	2	0	1	0	2	0	0	0	0	1	4	9
l	2	0	0	0	1	0	0	0	0	3	4	9
m	2	1	0	0	6	0	0	0	0	2	9	9
a	3	0	0	0	6	0	2	0	0	1	9	9
b	3	4	0	0	1	0	3	0	0	1	9	9
c	3	4	0	0	13	0	1	0	0	2	20	9
d	3	0	0	0	2	0	0	0	0	1	3	9
e	3	0	0	0	2	0	2	0	0	0	4	9
f	3	1	0	0	3	0	0	1	0	2	7	9
g	3	2	0	0	0	0	2	0	0	1	5	9
h	3	1	1	0	1	0	0	0	0	2	5	9
i	3	1	0	0	0	0	3	0	0	0	4	9
j	3	0	0	0	4	0	1	0	0	1	6	9
k	3	0	0	0	4	0	2	0	0	3	9	9
l	3	0	0	0	2	0	0	0	0	2	4	9
m	3	1	0	0	0	0	0	0	0	1	2	9
a	4	16	0	0	52	0	0	0	0	0	68	9
b	4	15	0	0	26	0	0	0	0	0	41	9
c	4	39	0	0	43	0	0	0	0	0	82	9
d	4	31	0	0	42	0	0	0	0	0	73	9
e	4	33	0	0	29	0	0	0	0	0	62	9
f	4	24	0	0	49	0	0	0	0	0	73	9
g	4	30	0	0	24	0	0	0	0	0	54	9
h	4	31	0	0	30	0	0	0	0	0	61	9
i	4	22	0	0	49	0	0	0	0	0	71	9
j	4	28	0	0	47	0	0	0	0	0	75	9
k	4	21	0	0	41	0	0	0	0	0	62	9

l	4	55	0	0	53	0	0	0	0	0	108	9
m	4	29	0	0	76	0	0	0	0	0	105	9
a	5	0	0	0	0	0	0	0	0	0	0	9
b	5	0	0	0	4	0	0	0	0	0	4	9
c	5	1	0	0	1	0	0	0	0	0	2	9
d	5	0	0	0	17	0	0	0	0	0	17	9
e	5	0	0	0	12	0	0	0	0	0	12	9
f	5	1	0	0	51	0	0	0	0	0	52	9
g	5	1	0	0	19	0	0	0	0	0	20	9
h	5	0	0	0	17	0	0	0	0	0	17	9
i	5	0	0	0	11	0	0	0	0	0	11	9
j	5	4	0	0	32	0	0	0	0	0	36	9
k	5	0	0	0	21	0	0	0	0	0	21	9
Transect	Station	*Scolelepis*	*Lumbrineris*	*Scoloplos*	Haustoriidae	*Ancinus*	*Emerita*	*Lepidopa*	*Austinixa*	*Donax*	N	S
l	5	3	0	0	22	0	0	0	0	0	25	9
m	5	0	0	0	7	0	0	0	0	0	7	9
a	6	1	0	0	1	0	0	0	0	0	2	9
b	6	1	0	0	0	0	0	0	0	0	1	9
c	6	1	0	0	0	0	0	0	0	0	1	9
d	6	1	0	0	0	0	0	0	0	0	1	9
e	6	0	0	0	0	0	0	0	0	0	0	9
f	6	0	0	0	0	0	0	0	0	0	0	9
g	6	0	0	0	0	0	0	0	0	0	0	9
h	6	0	0	0	0	0	0	0	0	0	0	9
i	6	0	0	0	0	0	0	0	0	0	0	9
j	6	0	0	0	0	0	0	0	0	0	0	9
k	6	0	0	0	0	0	0	0	0	0	0	9
l	6	0	0	0	0	0	0	0	0	0	0	9
m	6	0	0	0	0	0	0	0	0	0	0	9
a	7	0	0	0	1	0	0	0	0	0	1	9
b	7	0	0	0	0	0	0	0	0	0	0	9
c	7	0	0	0	15	0	0	0	0	0	15	9
d	7	0	0	0	0	0	0	0	0	0	0	9
e	7	0	0	0	0	0	0	0	0	0	0	9
f	7	0	0	0	2	0	0	0	0	0	2	9
g	7	0	0	0	0	0	0	0	0	0	0	9
h	7	0	0	0	0	0	0	0	0	0	0	9
i	7	0	0	0	0	0	0	0	0	0	0	9
j	7	0	0	0	0	0	0	0	0	0	0	9
k	7	0	0	0	0	0	0	0	0	0	0	9
l	7	0	0	0	0	0	0	0	0	0	0	9
m	7	0	0	0	0	0	0	0	0	0	0	9

Table D-5. Subtidal data from June 13, 2008.

Distance	Scolelepis	Lumbrineris	Magelona	Haustoriidae	Orchestia	Ancinus depressus	Lepidopa benedictii	megalopa	juv donax	copepod	mysid	sipunculida	N	S
-10	1			16		1					1		19	4
-20		1		30			1		3	1	1	1	38	7
-30	1			35	1	1			18		2	1	59	7
-40	1		1	2									4	3
-50	9			4									13	2
-60	2			10					1				13	3
-70				54		1		1					56	3
total	14	1	1	151	1	3	1	1	22	1	4	2	202	12
count	5	1	1	7	1	3	1	1	3	1	3	2	29	12

VITA

Name:	Angela Dawn Witmer
Address:	3258 TAMU, Department of Biology, Texas A&M University, College Station, TX 77843-3258
Email Address:	awitmer@live.com
Education:	B.S., Biology, New Mexico State University, Las Cruces, 1996 M.S., Biology, New Mexico State University, Las Cruces, 2001 Ph.D., Zoology, Texas A&M University, 2011