ANNUAL REPORT

Patterns of Shoreline Change and Hurricane Washover on Barrier Islands

Year 2

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INTRODUCTION

Despite the dynamic nature of barrier islands and spits, they have been highly developed and continue to be developed along much of the U.S. coast. This activity has altered erosional and depositional patterns of shorelines. Development has placed property and lives at risk from coastal storms, sea-level rise, and long-term erosion and has affected habitats for coastal ecosystems. This three-year project is designing new topographic surveying techniques and applying them to the study of the morphodynamics of these coastal zones. The Bureau of Economic Geology (Bureau) and the Center for Space Research (CSR) at The University of Texas at Austin are jointly conducting the research.

The primary field area includes 190 km of the southeast Texas coast (Fig. 1). This shoreline has both natural and developed areas, and its characteristics are typical for barrier coasts. Thus, techniques developed during this project can be applied to sandy barrier coasts around the world. We are coordinating three topographic surveying methods: (1) airborne laser altimeter surveys (also know as LIDAR surveys) provide continuous coverage of the dune and upper beach, (2) kinematic, three-dimensional (horizontal and vertical accuracy of several centimeters) GPS surveys using a vehicle provide coverage of the upper and lower beach, and (3) conventional total stations' surveys extend selected transects from landward of the foredune into the surf zone.. Overlap areas of the different survey data are compared to evaluate accuracy. We will merge these various data into an optimal digital elevation model.

The various survey data will be analyzed to reveal topographic and geomorphic relationships to past shoreline erosion and hurricane washover patterns. We will combine repeat surveys over a 3- to 4-year period with weather, wave, and water level data to develop process-response models of coastal change. We expect that we will find quantifiable relationships between coastal erosion patterns, wave refraction patterns, topography/bathymetry, and geomorphology. These relationships will provide guidance in predicting future shoreline change and storm hazards.

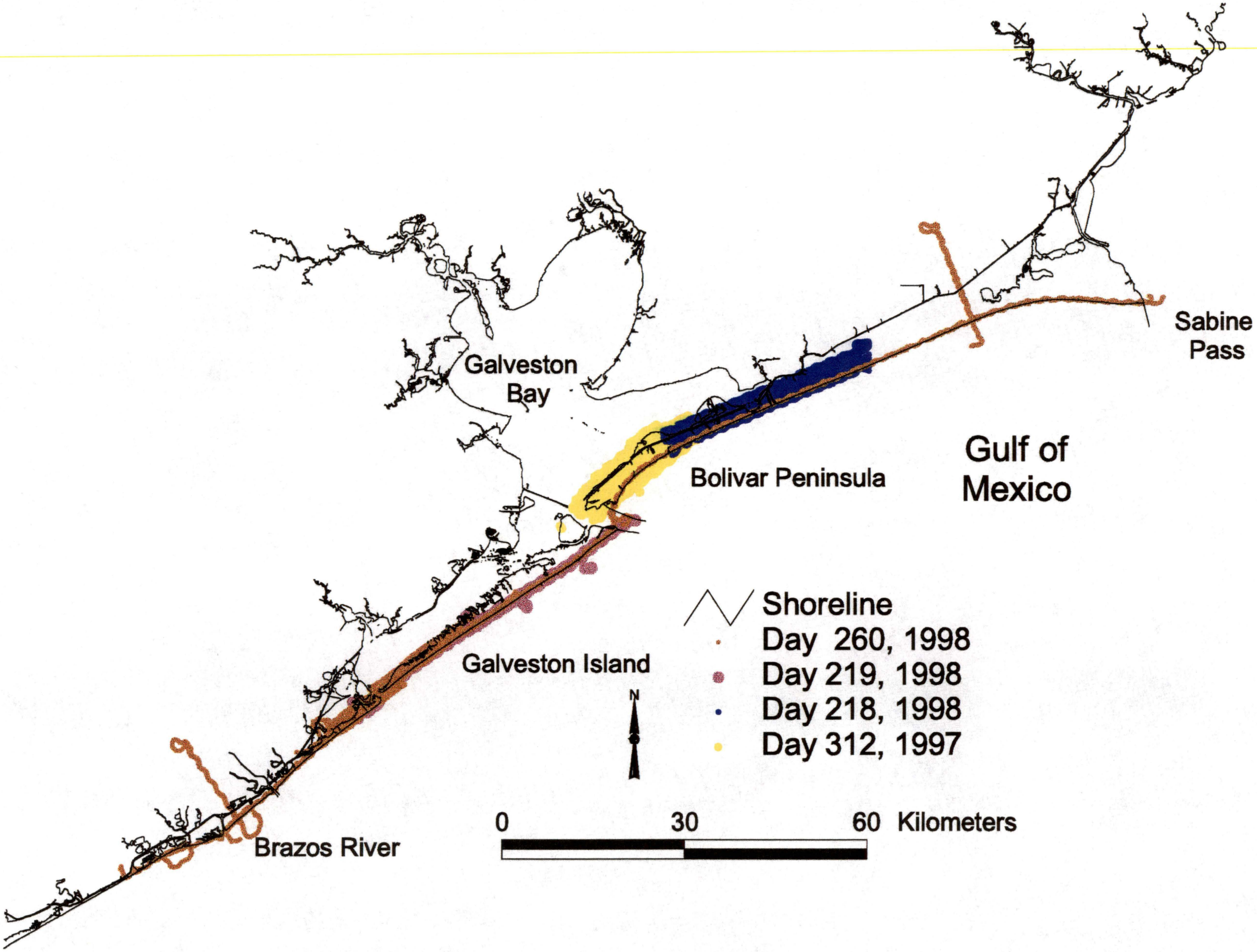


Figure 1. Location of ALTM surveys on the southeast Texas coast.

1999 FIELDWORK

LIDAR surveys were not conducted in 1999. Field schedules and access to an instrument made it impractical to conduct surveys at an optimum time. Optech Inc., the manufacturer of the LIDAR instrument, is working with the Bureau to conduct surveys in the spring of 2000 (See the year 1 report for a description of surveys conducted in 1997/98 and for a description of the Optech LIDAR instrument.). This survey will cover the entire Texas Gulf of Mexico shoreline, not just the southeast coast as had been planned for this project.

In 1999, ground surveys were conducted along Bolivar Peninsula to aid the interpretation of pre- and post-storm LIDAR data from 1998. Five beach profiles were measured and a 2-deminsional kinematic GPS survey was conducted of the shoreline. On August 22, 1998 Hurricane Bret made landfall on Padre Island along the south Texas coast. The Bureau responded to this major event with an over flight for oblique aerial photography on August 30 and ground surveys, including beach profiles and GPS shoreline and vegetation line surveys, from September 1 through September 3. This event provided researchers with insight to overwash processes, and the ground data set will aid the interpretation of a LIDAR survey to be acquired in the spring of 2000.

DATA ANALYSIS AND PRELIMINARY RESULTS

During 1999, analysis proceeded in two broad areas: (1) LIDAR data reduction including error analysis and the development of methods for creating topographic models and extracting information and (2) determining the patterns and causes of beach and dune change since 1994.

LIDAR Data Reduction and Analysis

Optech Inc. performed the initial processing of the 1998 LIDAR data to compute x, y, and z data points. The Bureau and CSR computed aircraft GPS trajectories for comparison with Optech-computed GPS trajectories and for use in the ground point solutions. The Bureau also determined the position of the GPS ground reference stations with respect to local tidal datums and compared kinematic GPS road surveys and beach profile surveys to estimate the accuracy of LIDAR surveys. The road surveys were also used to determine the bias error of each LIDAR survey so that they could be adjusted to allow temporal comparisons. The Bureau and CSR are continuing to construct Digital Elevation Models and topographic profiles from the LIDAR data.

Accuracy

During the first year of this project, we determined the accuracy of LIDAR data by point-to-point comparisons with GPS kinematic road surveys (Gutierrez et al., 1998). Those comparisons showed vertical RMS values of 12 to 15 cm for the LIDAR data. During the second year, we began comparisons of ground-surveyed beach profiles with profiles constructed from LIDAR data. Figure 2 is a comparison between ground-surveyed beach profiles and beach profiles constructed from two swaths of LIDAR data before and after Tropical Storm Frances in 1998. Data points that fall within 2 m on each side of the ground-surveyed profile line form the LIDAR profiles. Points interpreted on the LIDAR profiles as ground points agree to within 15 cm of the ground-surveyed points.

A significant discrepancy between the LIDAR and ground profile occurs on the berm and beachface for one of the LIDAR passes before Tropical Storm Frances (Fig. 2a). We think this discrepancy was caused by a spot of oil on the window of the laser altimeter that caused anomalous data points in the portion of the data swath directly under the aircraft. For one of the LIDAR passes, the anomalous data occurred offshore and did not affect the beach data. Relatively thick vegetation on the landward side of the primary foredune is evident in the LIDAR data. Here, some of the laser shots reflected from the top of the vegetation and some penetrated the vegetation and reflected from the ground. The laser energy does not penetrate water; thus the water surface is apparent on the LIDAR profiles. Other differences between the LIDAR and ground surveys are caused by natural variation to each side of the profile. This is particularly evident in the post-Frances profile where a picnic shelter was measured (Fig. 2b). In summary, it is apparent that LIDAR can measure beaches and dunes with enough accuracy and detail to make significant advances in mapping the foredunes and beaches, assessing the coast for susceptibility to storm damage, and measuring the effects of storms.

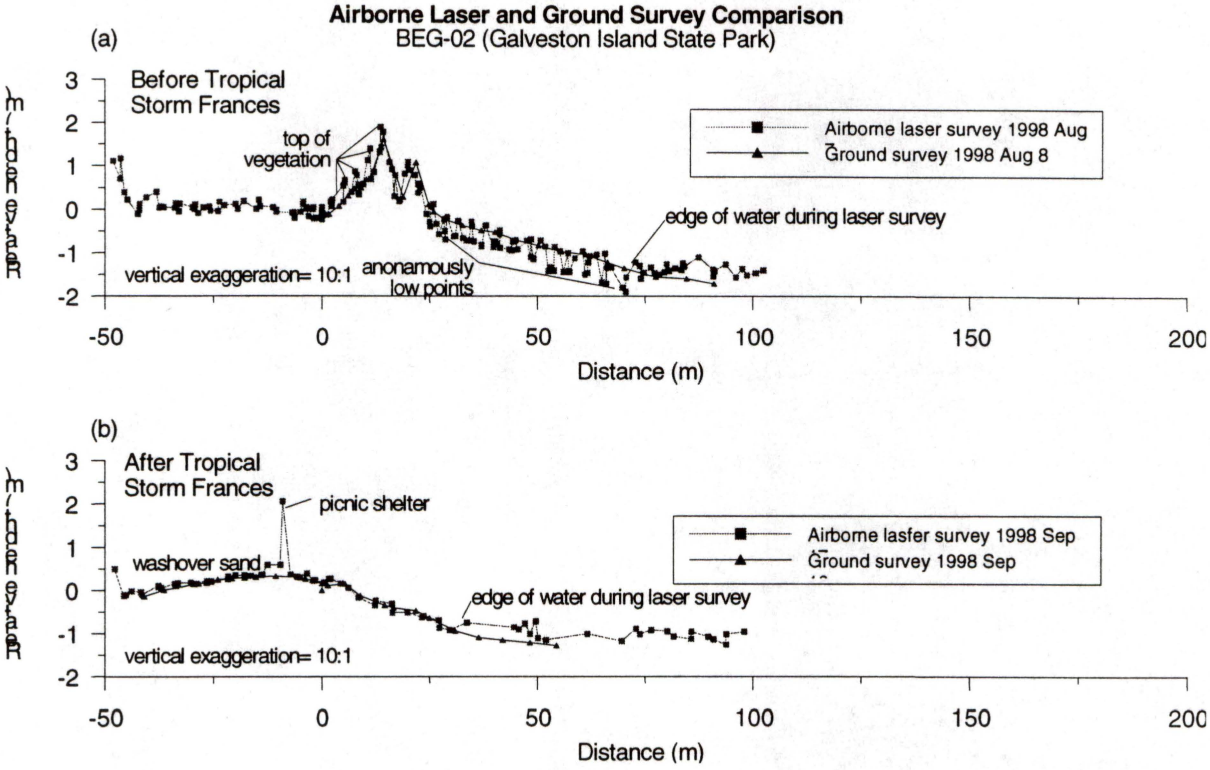


Figure 2. Beach profile comparisons of airborne LIDAR and ground surveys at Galveston Island State Park, profile BEG-02: (a) before Tropical Storm Frances; (b) after Tropical Storm Frances.

DEM Construction and Shoreline Extraction from LIDAR Data

In September 1998, Tropical Storm Frances struck the southeast Texas coast. In the vicinity of Rollover Pass on the Bolivar Peninsula we had acquired a LIDAR survey of the beaches and dunes in August before the storm and again one-week after the storm. These surveys allow the characterization of the response of the beach to a major erosional event. Before comparisons can be made, however, the data must be transformed into a common reference frame that is preferably related to sea level. The horizontal and vertical formats of the LIDAR surveys were Universal Transverse Mercator (UTM) coordinates and heights above the WGS-84 reference ellipsoid (HAE). All the ellipsoid heights were first transformed into orthometric heights using the National Geodetic Survey G96sss geoid model. A –35-cm vertical bias was then removed from all the data so that the zero-elevation would conform to the local mean sea level as measured at the Port Bolivar tide gauge.

Pre- and post-Frances digital elevation models (DEM) were computed from the vertically adjusted data sets. The DEM's are uniform, 2 m × 2 m grids interpolated from the LIDAR observations using a minimum curvature algorithm. The DEM's represent 20 km of the Bolivar shoreline centered on Rollover Pass. A portion of the DEM's are shown in figure 3. The colors in the LIDAR maps indicate variations in elevation above or below mean sea level. Superimposed on the image are the +1-m elevation contour lines for the pre-Frances DEM (black contour line) and the post-Frances DEM (red contour line). To estimate the shoreline change caused by Frances, the +1-m contour lines were digitized by hand. The lines were digitized on a computer display with the high-resolution topographic images in the background. The background images allowed the removal of variations in the contour lines caused by man-made structures on the beach. Figure 4 shows shoreline change caused by Tropical Storm Frances as derived by comparing the +1-m contour lines. This plot readily shows the widespread erosion and the complicated alongshore pattern of erosion caused by Frances.

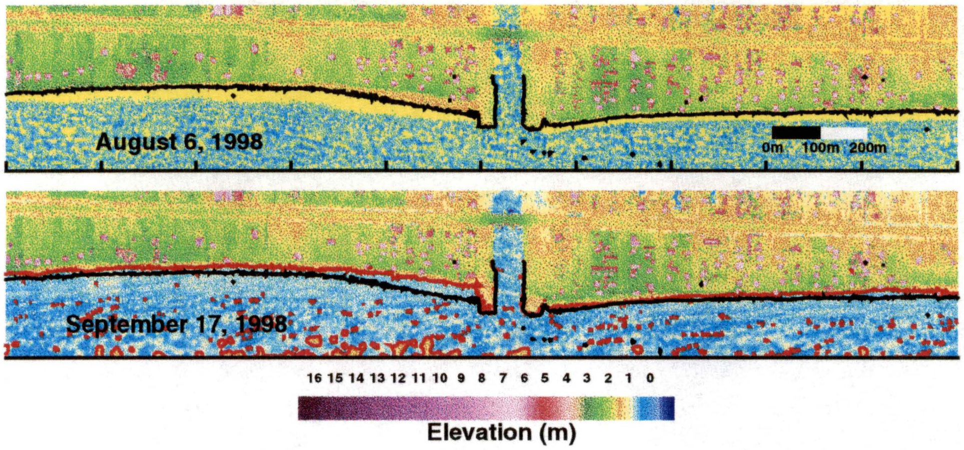


Figure 3. Portions of DEM's created from LIDAR surveys before and after Tropical Storm Frances. The Gulf of Mexico is to the bottom of each image, and Rollover Pass, with a highway bridge spanning it, is in the center. Elevations are related to mean sea level. The black line is the +1 m contour line before Frances, and the red line is the +1 m contour line after Frances.

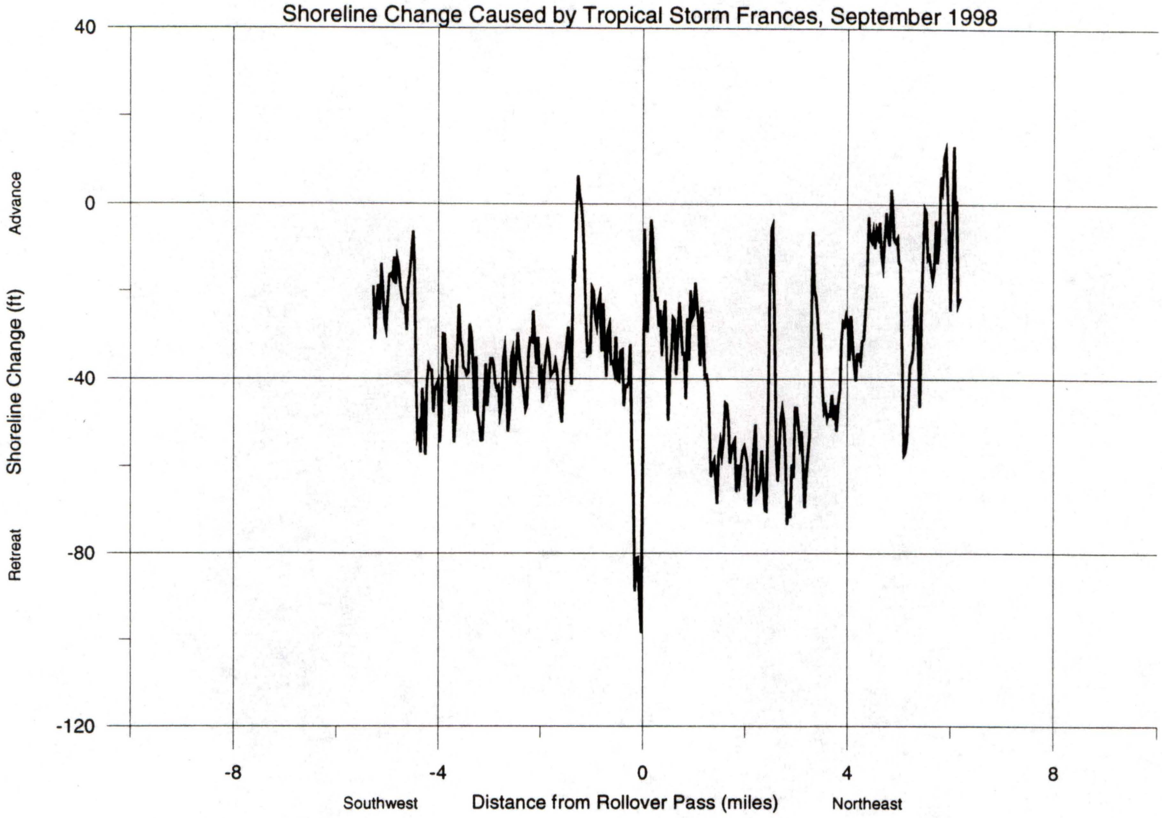


Figure 4. Shoreline change caused by Tropical Storm Frances, September 1998. Data are from LIDAR survey and change is movement of the 1 m (3.3 ft) above mean sea level contour line.

Patterns and Causes of Beach and Dune Change since 1994

During the passage of Tropical Storm Josephine in October 1996, the dunes and beaches along the southeast Texas coast significantly eroded and put many structures at risk of failure. In September 1998 Tropical Storm Frances caused even greater erosion and destruction. To characterize the responses of beaches and dunes to these tropical storms, comparisons between ground and LIDAR beach surveys, water level, and wave data were made.

Methods

In November 1997, we resurveyed 32 dune and beach topographic transects established in 1994 as part of the Texas Natural Resources Inventory (Fig. 5). Subsets of these transects were surveyed in 1995, 1996, and before and after Tropical Storm Frances in

1998 (Table 1). These transects, from here on referred to as beach profiles, begin from a temporary datum marker behind the foredune or scarp and continue along a path oriented perpendicular to the shoreline to wading depth. An electronic total station was used to measure heights relative to the datum marker, and the horizontal and vertical positions of the markers were determined using geodetic Global Positioning System techniques. Points along the profile were measured where there were changes in slope and at important features such as the vegetation line and the boundary between dry and wet sand.

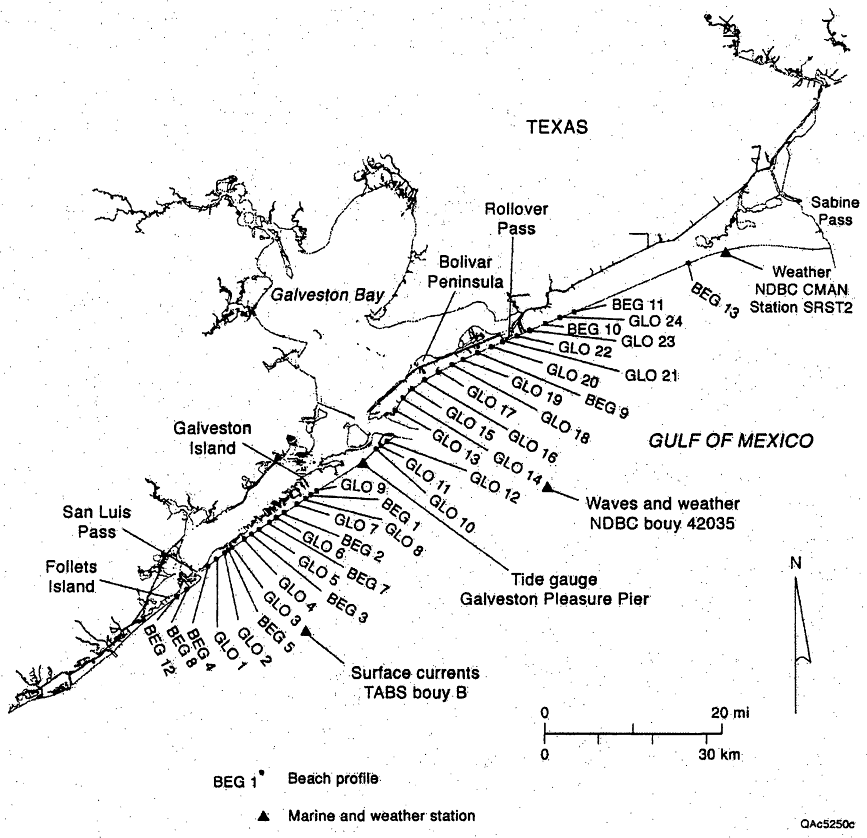


Figure 5. Southeast Texas coast showing beach profile and oceanographic and meteorological stations. The NDBC CMAN station is a coastal weather station located at Sea Rim State Park and operated by the National Data Buoy Center. The station provides hourly wind direction and speed as well as other standard weather measurements. The NDBC buoy records weather observations and non-directional wave data. The tide gauge at the Galveston Pleasure Pier is operated by the Blucher Institute of Texas A&M University at Corpus Christi for the National Oceanic and Atmospheric Administration. This station records water levels and standard deviations of the water levels. The station also records weather observations. The TABS (Texas Automated Buoy System) buoy is operated by Texas A&M University for the Texas General Land Office. This buoy records surface current direction and speed.

Table 1. Beach profiles measured along the upper Texas coast from September 1994 to March 1999. See figure 5 for profile locations.

Profile name	Date (year, month, day)
BEG01	940913,960624, 971111
BEG02	940913, 950427, 960624, 971001, 971111, 971209, 980428, 980808, 980916, 981007, 981022, 981203, 990302
BEG03	940910, 950427, 971112
BEG04	940911, 950426, 971112, 980915
BEG05	940914, 971113, 980916
BEG07	940914, 960624, 971112
BEG08	940914, 950430, 960616, 961026, 970906, 970920, 971112, 971209, 980428, 980809, 980915, 981022, 981203, 990302,
BEG09	940925, 950428, 971109,
BEG10	940926, 971110,
BEG11	971110
BEG12	971113, 980916
BEG13	980415
GLO01	940911, 971112, 980916
GLO02	940911, 950428, 971112
GLO03	940911, 971112
GLO04	940911, 971112, 980808, 980916
GLO05	940910, 971112
GLO06	940910, 971111
GLO07	940913, 960624, 971111
GLO08	940913, 971113
GLO09	940913, 971111, 980916
GLO10	940912, 971111
GLO11	940912, 971111
GLO12	940912, 971111,
GLO13	940925, 950429, 971109, 980417
GLO14	940925, 971109
GLO15	940925, 950430, 971109
GLO16	940925, 971109
GLO17	940927, 950429, 971109
GLO18	940927, 971109
GLO19	940925, 971109
GLO20	940926, 950430, 971110, 980918
GLO21	940926, 971110
GLO22	940926, 971110, 980918
GLO23	940926, 971110
GLO24	940926, 971110, 980918

Beach and dune volume was determined by calculating the area of the profile above an elevation that is approximately mean low tide. An assumption was made that the profile was uniform 0.5 m to each side, hence the profile area is multiplied by 1 m to yield the volume of a slice of the beach. Volume is expressed as cubic meters per meter of shoreline. The computer program "Beach Morphology Analysis Package" (BMAP) developed by the U. S. Army Corps of Engineers was used for the volume calculations. The position of the shoreline along each profile was generally picked as the upper berm crest, but some profiles had no discernable crest. To aid the interpretation of the shoreline position for profiles without a distinct berm crest, all profiles in the time series were graphed on the same plot, and profiles with berm crests guided where the shoreline should be picked for profiles without berm crests. The elevation of the shoreline picked on the profiles may vary by as much as 0.5 m between the surveys of a given profile. The vegetation line was recorded in the field as the seaward most point from which vegetation spreads continuously landward.

Data on waves, water level, wind, and surface currents were acquired for the entire period from 1994 to 1998 or just for particular storm events depending on the type of data. Locations of the various meteorological and oceanographic stations from which data were acquired are shown in figure 5. Tropical storm and hurricane tracks and wind velocities were obtained from the National Hurricane Center (Figs. 6 and 7). Data were analyzed and compared to changes in the beach profiles.

Results

Beach profiles, 1994 to 1997

A comparison of the 1994 and 1997 transects shows that from the Galveston seawall to 4-km northeast of San Luis Pass the vegetation line moved landward 5 to 15 m (Fig. 8a). Within 4 km of San Luis Pass, large shifts in the position of the vegetation line occurred. Within a kilometer of the pass, the vegetation line advanced seaward 35 m, but just 1 to 3 km northeast of the pass it retreated 22 m. The amount of vegetation line retreat was relatively small for a portion of West Beach in an area 11 to 15 km to the northeast of San Luis Pass (GLO-04 and BEG-03 area). Here retreat was only about 5 m. Vegetation line retreat was greater nearer the Galveston Seawall. One profile about 6-km southwest of San Luis Pass on Follets Island (BEG-08) experienced 11 m of vegetation line retreat. Along East Beach on the east end of Galveston

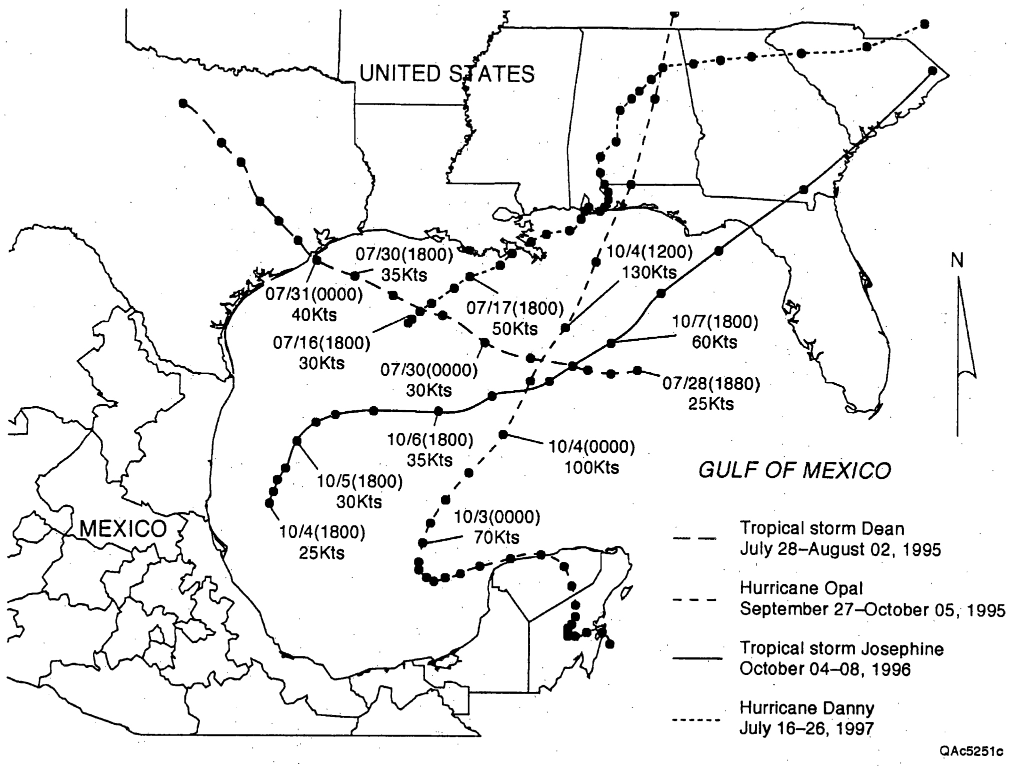


Figure 6. Wind speeds and tracks of tropical storms and hurricanes that affected the northwestern Gulf of Mexico from 1994 to 1997. No storms occurred in 1994.

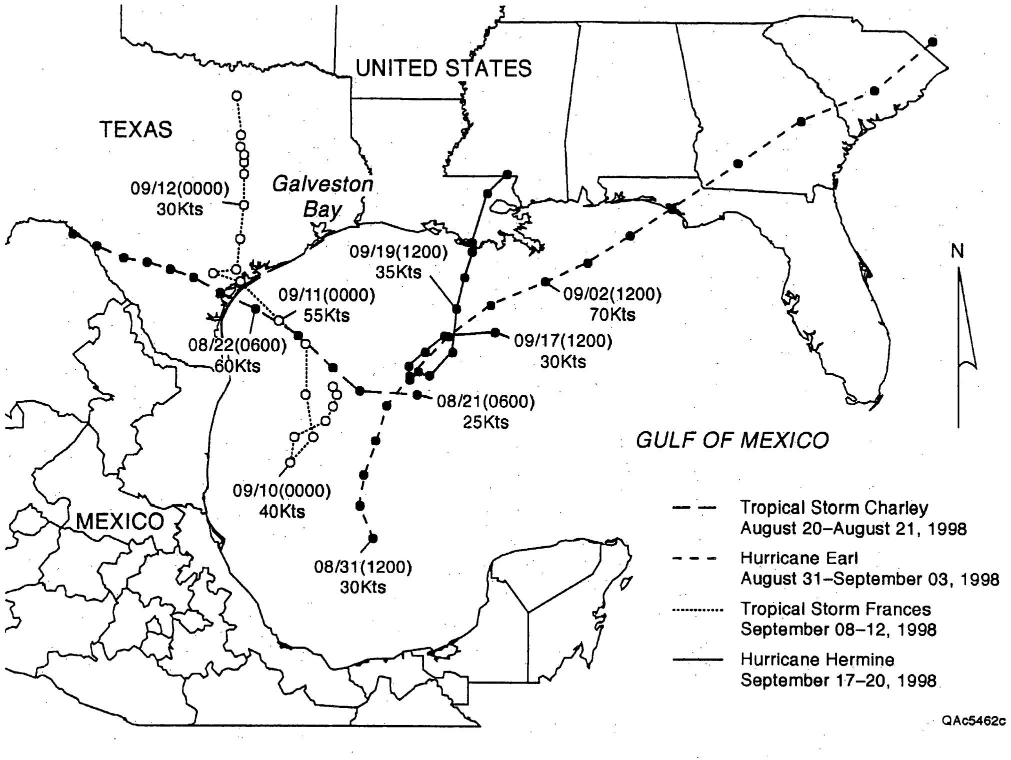


Figure 7. Wind speeds and tracks of tropical storms and hurricanes that affected the northwestern Gulf of Mexico in 1998.

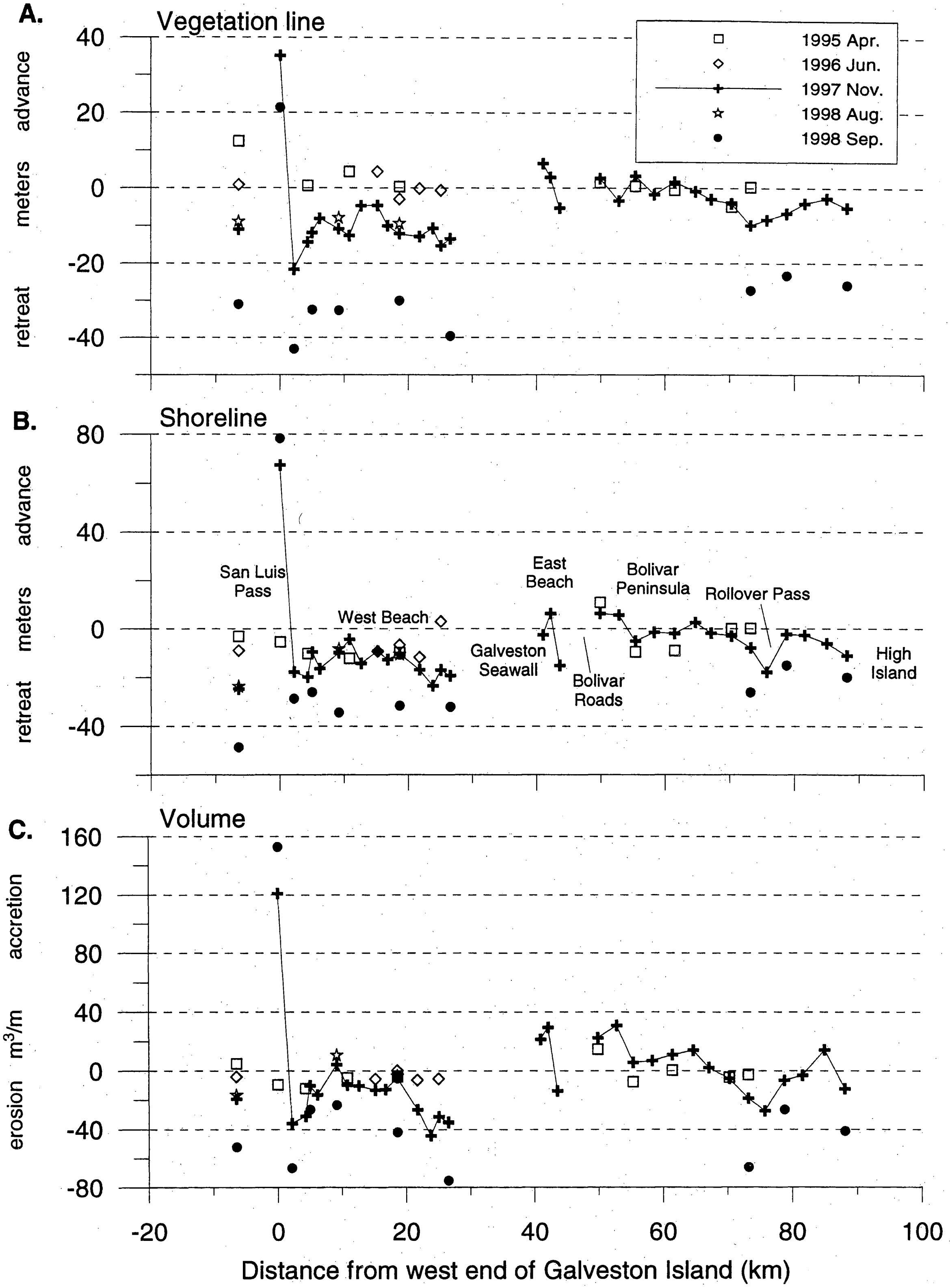


Figure 8. Cumulative change in beach profiles since September 1994: (A) vegetation line movement; (B) shoreline movement; and (C) profile volume change.

Island, the vegetation line advanced 3 to 6 m but retreated 5 m at a location closer to the jetties. On Bolivar Peninsula, 7 to 10 m of retreat occurred within several kilometers of Rollover Pass. The vegetation line remained relatively stable along the rest of Bolivar Peninsula.

Shoreline change from 1994 to 1997 (Fig. 8b) generally followed the same pattern as vegetation line change. Along West Beach and northern Follets Island except just northeast of San Luis Pass, the shoreline moved 4 to 23 m landward. Within a kilometer northeast of San Luis Pass, the shoreline advanced 67 m. On East Beach, the shoreline retreated 15 m at the eastern most location. The shoreline remained stable along western Bolivar Peninsula but retreated 18 m within 2 to 3 km southwest of Rollover Pass. The Shoreline was stable northeast of Rollover Pass but retreat increased to 11 m at High Island.

Sand volume also had generally the same pattern of change from 1994 to 1997 as the vegetation line and shoreline (Fig. 8c). The alongshore trends, however, were more pronounced. Loss of sand within 10-km southwest of the Galveston seawall exceeded 40 m^3/m. Along the relatively stable portion of West Beach away from the seawall, sand loss was less than 15 m^3/m, and at one location there was a small gain of sand (GLO-04). The same swings occurred in sand volume in the vicinity of San Luis Pass as occurred in the shoreline and vegetation line positions. The Follets Island profile, southwest of San Luis Pass, decreased in volume by 19 m^3/m. Two of the East beach profiles increased in volume, but the eastern most one decreased by 14 m^3/m. The beaches along the western Bolivar peninsula gained sand as did a location about 7 km northeast of Rollover Pass. For about 5-km southwest of Rollover Pass, the amount of sand loss reached 27 m^3/m.

Along Follets and Galveston Islands, the beaches in 1994 had a prominent berm and generally a convex profile shape. In November 1997, this berm had eroded, and the beach profiles seaward of the dune were generally linear or concave in shape. Erosion also either cut back or eroded completely incipient foredune deposits (low, discontinuous, vegetated mounds) mostly made up of sand that had been scraped from the beach and pushed up in front of the primary foredune or against a back-beach scarp. An exception to this change in beach shape along West Beach is the area adjacent to San Luis Pass (BEG-04) where a large amount of accretion occurred in the form of berm widening and new natural foredune growth. Furthermore, in the relatively stable area in the vicinity of GLO-04 and BEG-03, the 1994 berm was eroded and the shoreline moved landward, but this erosion was offset by foredune growth landward of the 1994 vegetation line. Sand eroded from the berm may have been incorporated into the expanded foredune. Scarp retreat occurred northeast of San Luis Pass at GLO-01 and southwest of the Galveston seawall at GLO-09 and BEG-01.

Along the western portion of Bolivar Peninsula from GLO-13 to BEG-09, sand volume increased during the period from 1994 to 1997. The increase involved foredune growth (both natural and unnatural from beach scraping) and back-beach aggradation but not significant berm widening. From BEG-09 to Rollover Pass and just east of Rollover Pass at GLO-22, the beaches lost sand in the form of scarp retreat. In 1997, back-beach scarps 1- to 1.5-m high were present. At BEG-10, 8.5 km east of Rollover Pass, a large amount of sand in the form of artificial foredune growth (piles of sand scraped from the beach and pushed into piles) and vertical berm aggradation was added from 1994 to 1997. This location is within the influence of a pier 200 m to the northeast. The pier has caused a bulge in the shoreline extending about 200 m to each side. Farther to the northeast at GLO-24, the prominent 1994 berm and half of the foredune had been eroded by 1997.

Subsets of the profiles were measured in April 1995 and June 1996 (Table 1). These profiles show that particularly with respect to vegetation line movement and profile volume not much happened from September 1994 to the summer of 1996 before Tropical Storm (TS) Josephine struck in October 1996 (Fig. 6). An exception to this is the more than 10 m of vegetation line advance at BEG-08 on Follets Island from 1994 to 1995. Shoreline movement was more variable and probably shifted back and forth during this period at a greater frequency than can be described by these data. Based on these data and field observations after TS Josephine, it is clear that TS Josephine caused the vegetation line retreat and sand volume loss between 1994 and 1997.

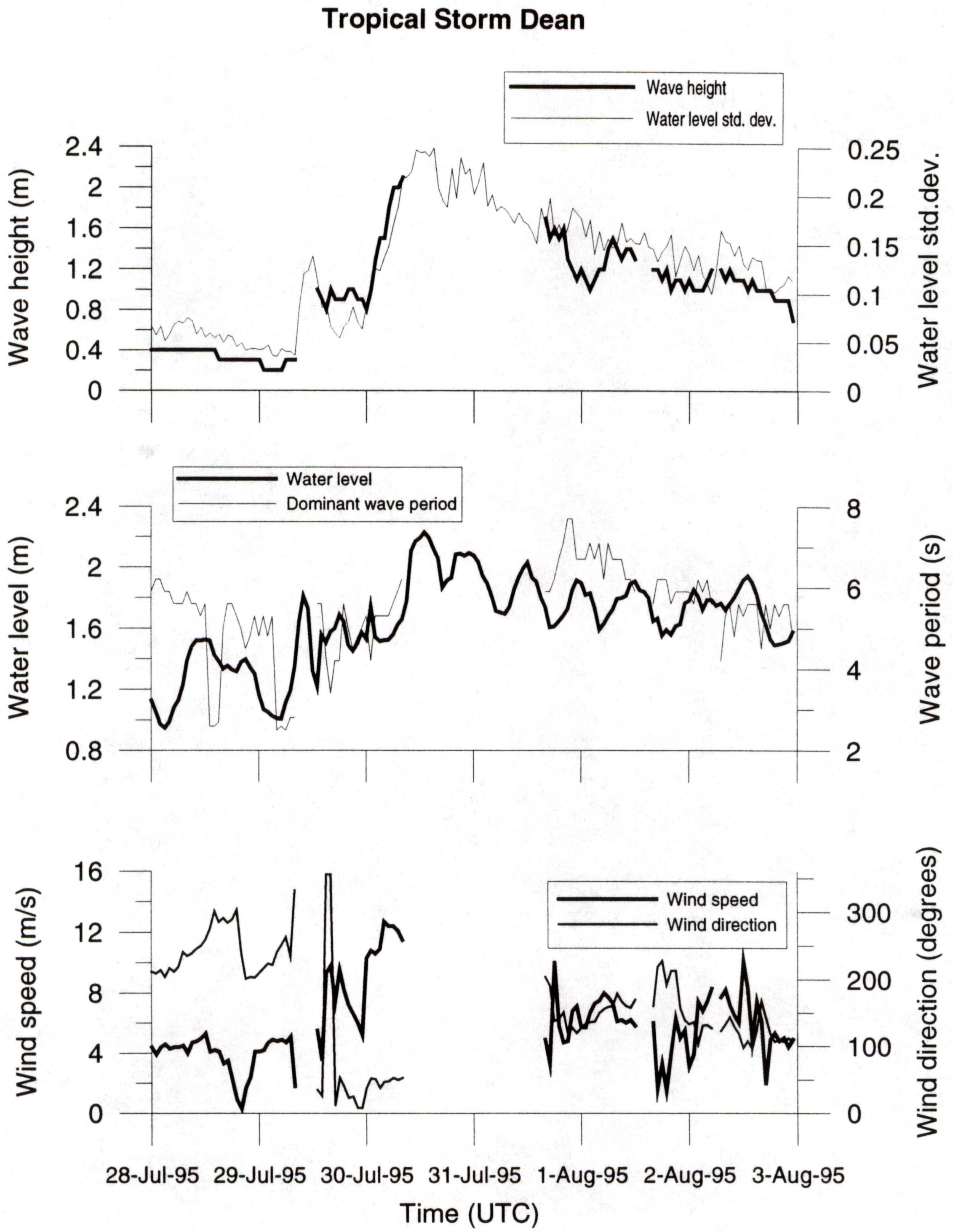
Beach profiles before and after TS Frances in 1998

Whereas TS Josephine in 1996 caused 5 to 15 m of vegetation line retreat, TS Frances caused 15 to 25 m of retreat (Fig. 8a). It should be noted that the profiles used here to gauge the effects of TS Josephine were measured 1 year after the storm, whereas the TS Frances profiles were measured 1 week after the storm. Nevertheless, it is clear that TS Frances had a much greater effect on the beaches than Josephine. On West Beach from the seawall to west of Galveston Island State Park the foredunes were completely eroded. The foredune and incipient foredune at Galveston Island State Park (BEG-02) were flattened with a portion of the sand washed landward into the picnic area. Father to the west, in the area of GLO-04, piles of vegetated sand in front of the natural foredune were completely eroded, but the foredune survived. Farther to the west at GLO-01, a scarp that had been cut back by Josephine in 1996 retreated an additional 25 m. Next to San Luis Pass at BEG-04, the vegetation line also retreated, but the beach still had more sand than it did in 1997 (Fig. 8c). On Follets Island at BEG-08, the foredune completely eroded, but a prominent foredune ridge that was 50 m landward of the foredune survived.

Storms from 1994 to 1998

Figures 6 and 7 are maps showing the tracks of tropical storms and hurricanes that affected the northwestern Gulf of Mexico from 1994 to 1998. None of the eight storms occurred in 1994. Only TS's Josephine and Frances caused significant beach erosion and property damage on the upper Texas coast, but other storms had tracks just as close or closer to the study area as Josephine and Frances. Figures 9 through 14 are graphs for six of the storms showing wave height and period, and wind speed and direction from NDBC buoy 42035 (Fig. 5), and water level standard deviation (WLSD) from the open-coast tide gauge at the Galveston Pleasure Pier (Fig. 5).

The water level at the tide gauge is computed by smoothing 181 1-second readings. The standard deviation of these 181 readings are higher during high waves which cause high-amplitude water-level variations. Therefore, the WLSD measured by the tide gauge correlates with the wave heights measured by the buoy and can provide a surrogate measurement of wave height. This is especially useful when buoy data are not available.



Tropical Storm Dean

Figure 9. Winds, water levels, and waves during Tropical Storm Dean. Water level and water level standard deviation are from the Pleasure Pier open-coast tide gauge, wave and wind data are from a moored buoy operated by the National Data Buoy Center offshore Galveston Bay. See figure 5 for station locations.

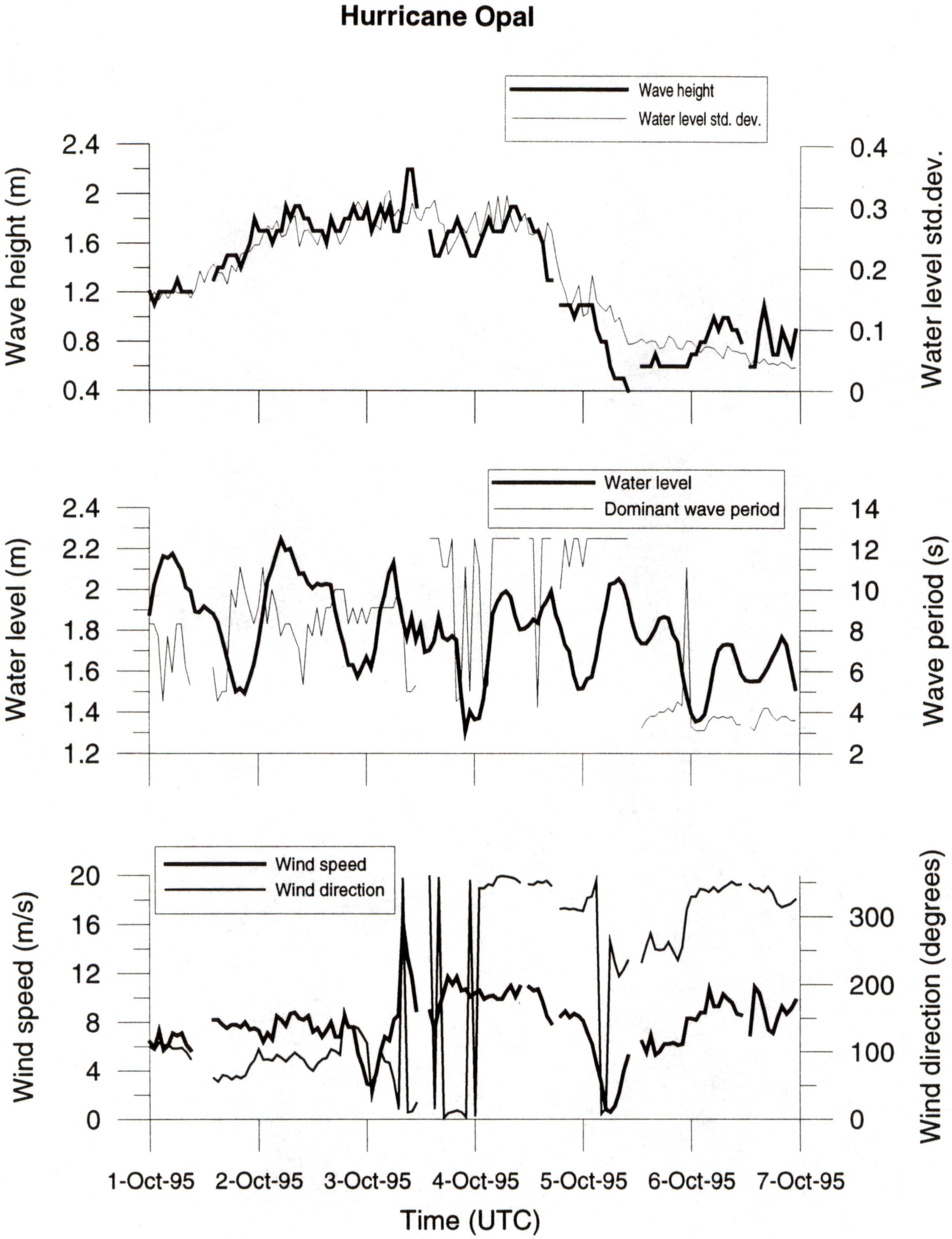


Figure 10. Winds, water levels, and waves during Hurricane Opal. Water level and water level standard deviation are from the Pleasure Pier open-coast tide gauge, wave and wind data are from a moored buoy operated by the National Data Buoy Center offshore Galveston Bay. See figure 5 for station locations.

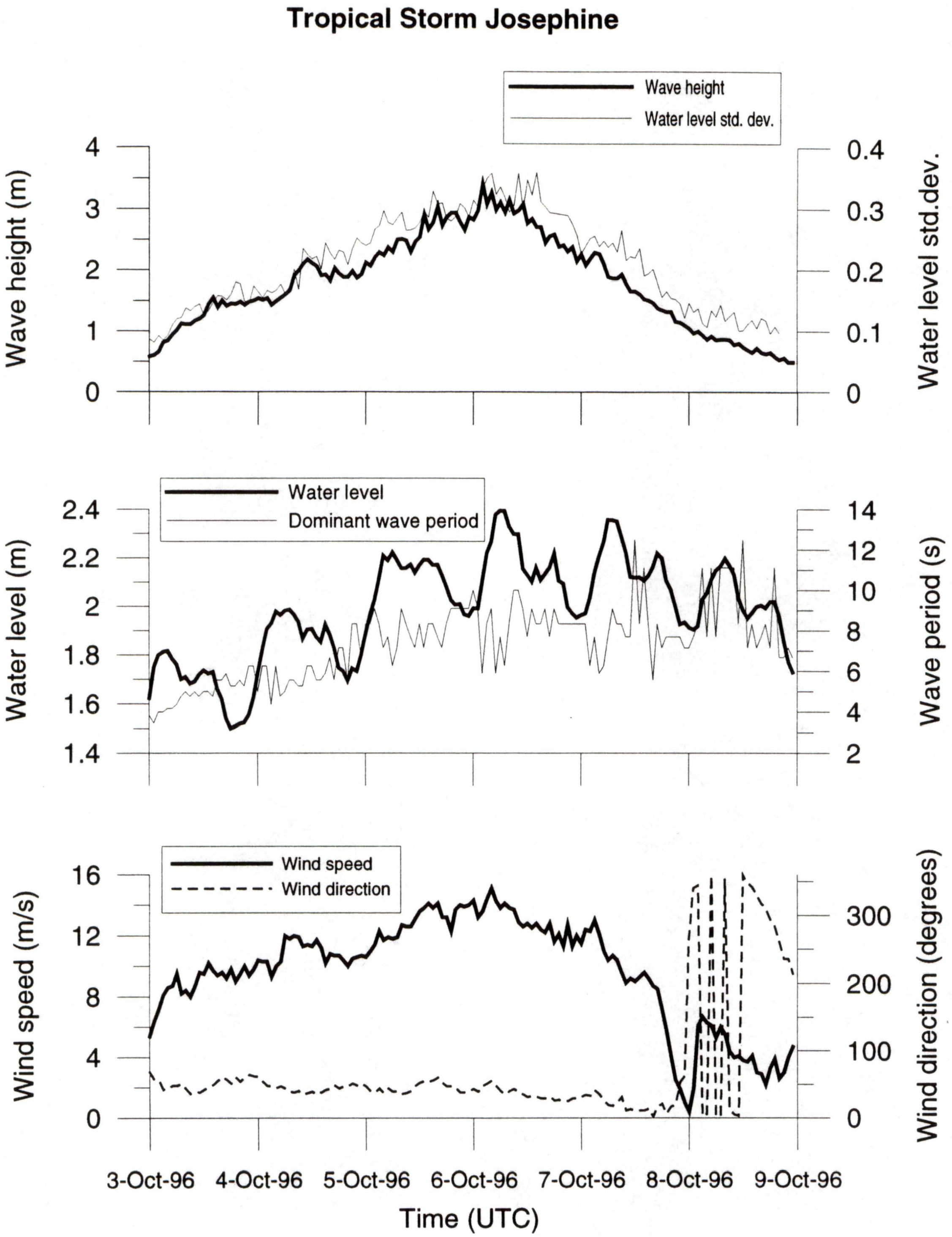


Figure 11. Winds, water levels, and waves during Tropical Storm Josephine. Water level and water level standard deviation are from the Pleasure Pier open-coast tide gauge, wave and wind data are from a moored buoy operated by the National Data Buoy Center offshore Galveston Bay. See figure 5 for station locations.

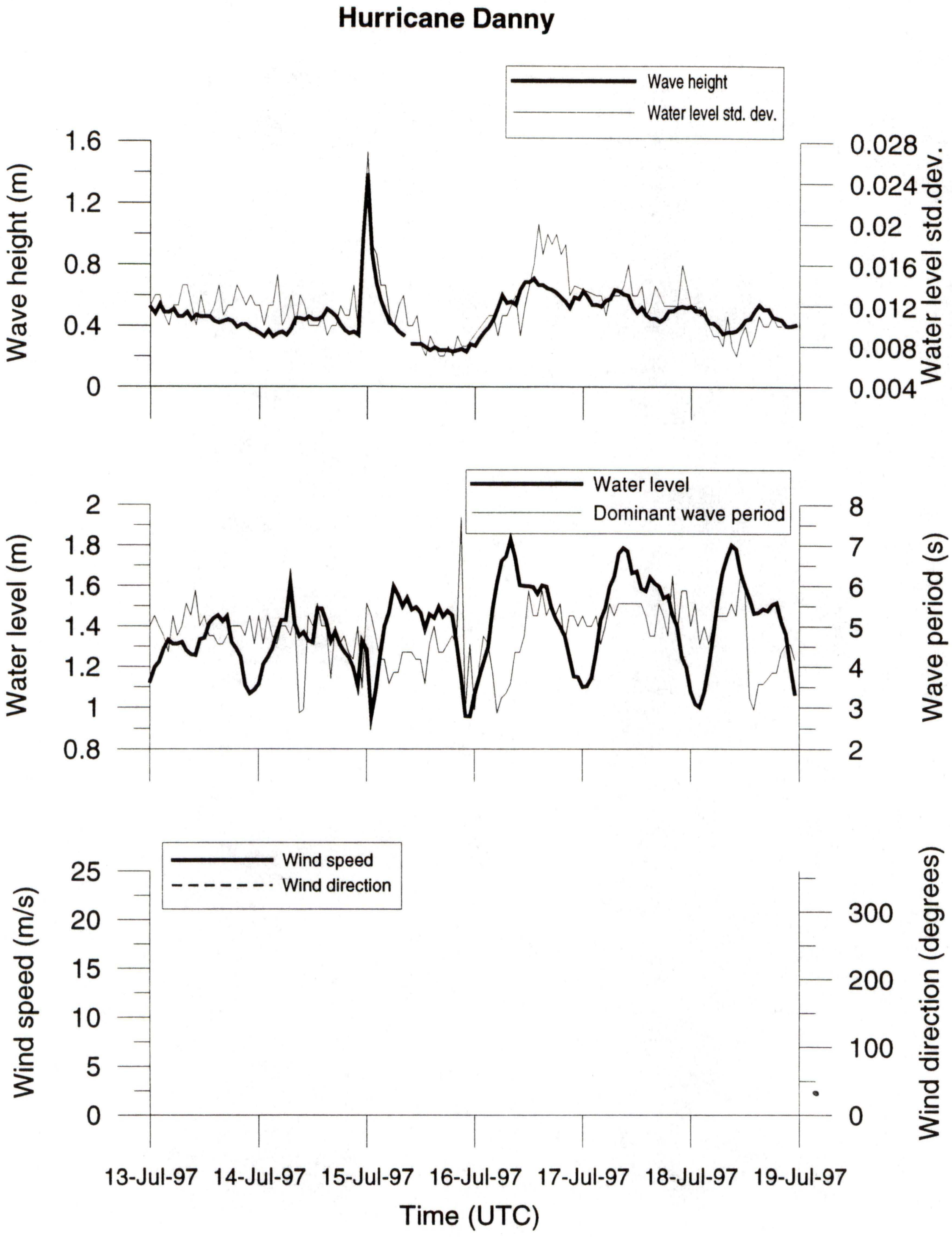


Figure 12. Winds, water levels, and waves during Hurricane Danny. Water level and water level standard deviation are from the Pleasure Pier open-coast tide gauge, wave and wind data are from a moored buoy operated by the National Data Buoy Center offshore Galveston Bay. See figure 5 for station locations.

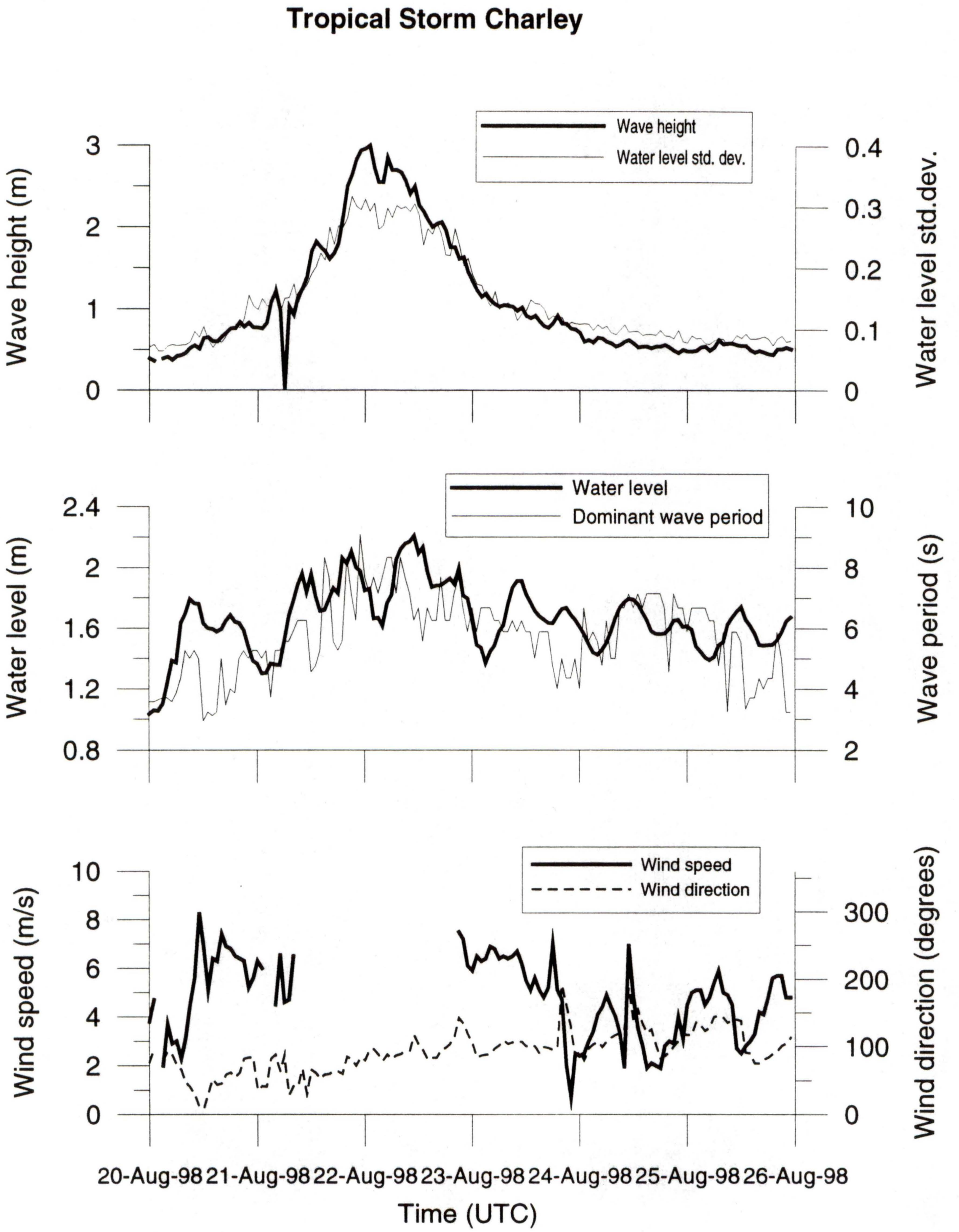


Figure 13. Winds, water levels, and waves during Tropical Storm Charley. Water level and water level standard deviation are from the Pleasure Pier open-coast tide gauge, wave and wind data are from a moored buoy operated by the National Data Buoy Center offshore Galveston Bay. See figure 5 for station locations.

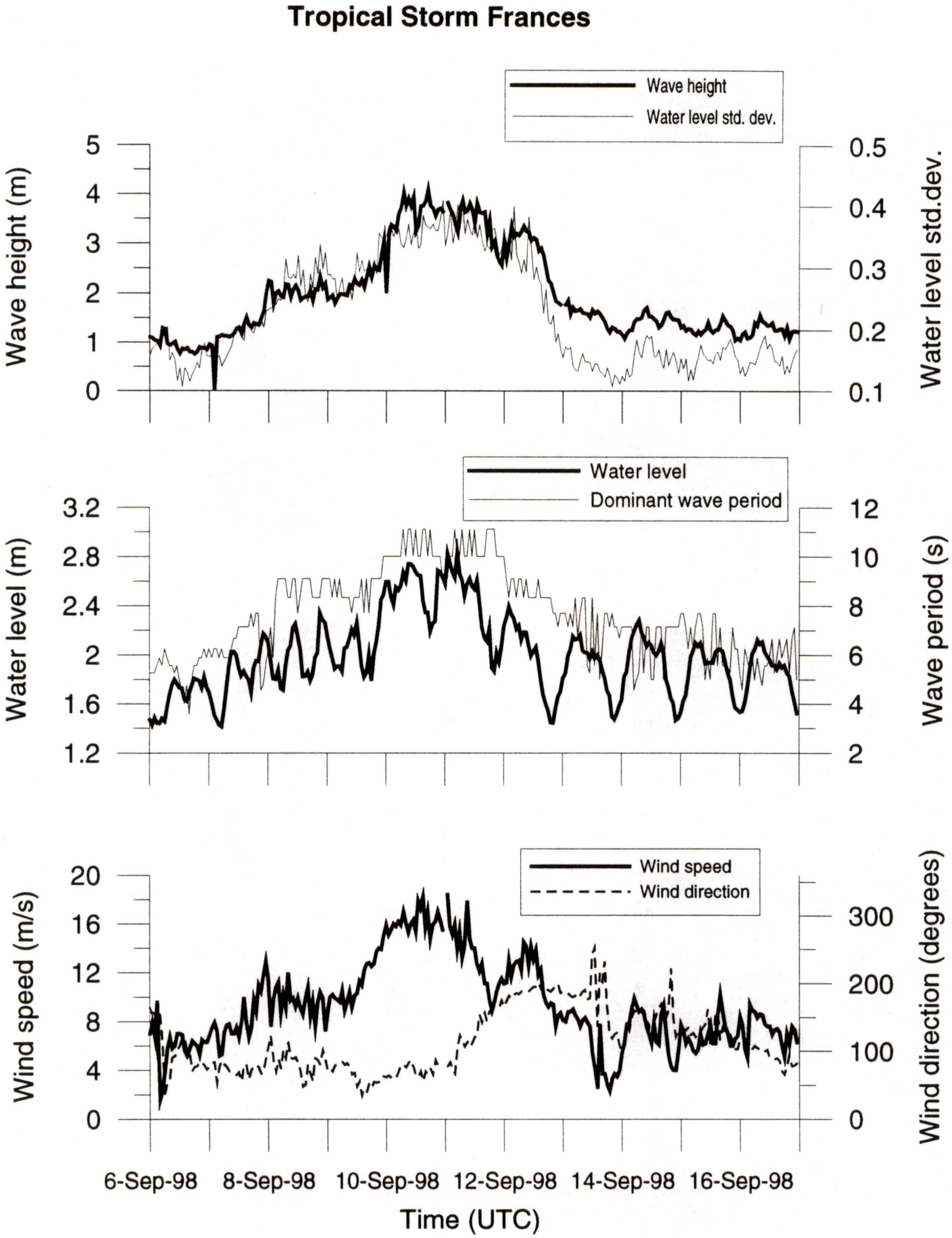


Figure 14. Winds, water levels, and waves during Tropical Storm Frances. Water level and water level standard deviation are from the Pleasure Pier open-coast tide gauge, wave and wind data are from a moored buoy operated by the National Data Buoy Center offshore Galveston Bay. See figure 5 for station locations.

The key parameters of peak water level, peak WLSD, and peak wave height are presented in table 2. For each of these parameters, the average and standard deviations of the hourly readings of the entire time series from 1993 through November 1998 were computed. Table 2 presents the number of hours that the water level, wave height, and WLSD exceeded the value that is three times the standard deviation above the average. These values are considered extreme conditions for this coast.

Table 2: Water levels and wave heights during storms. Water levels were recorded by the Pleasure Pier tide gauge and are referenced to the station datum. Wave heights were recorded by the offshore NDBC buoy #42035. Values for which durations are given are three times the standard deviation above the average of the parameter's time series from 1993 to September 1998. See figure 5 for station locations.

Parameter	TS Dean July 1995	HU Opal October 1995	TS Josephine October 1996	HU Danny July 1997	TS Charley August 1998	TS Frances September 1998
Peak water level (m)	2.23	2.25	2.40	1.83	2.21	2.83
Peak wave height (m)	No data	2.20	3.41	1.39	3.00	4.09
Peak water level standard deviation (WLSD) (m)	0.249	0.326	0.360	0.027	0.317	0.410
Hours water level > 2.18 m	3	4	25	0	1	64
Hours wave height > 2.30 m	No data	0	40	0	16	73
Hours WLSD > 0.26 m	0	40	49	0	23	111

Tropical Storms Josephine and Frances standout from the other storms most notably in the duration of the extreme conditions. Peak water level during Josephine exceeded Dean's, Opal's, and Charlie's water levels by less than 20 cm. However, high-water levels lasted for 25 hours during Josephine versus 4 hours or less for the other storms. The duration of Josephine also allowed high waves to develop. Waves during Josephine were more than 1-m higher than during Dean and Opal and extreme wave heights lasted for 49 hours compared to 0 hours for Dean and Opal. However, extreme WLSD values lasted for 40 hours during Opal, which reflects the long-period swells that arrived at the coast from this distally tracking hurricane. During TS Charley in 1998, waves peaked at 3 m and extreme wave conditions lasted for 16 hours, but the high waves were not coincident with high-water levels. Hurricane Danny in 1997 did not create extreme conditions. Data for Hurricane Earl and TS Hermine (Fig. 7) in 1998 are not presented here, and these storms did not cause significant beach or dune changes.

TS Frances in September 1998 caused large beach and dune changes and created the most extreme conditions of all the storms that affected this coast from 1994 to 1998. Peak water level exceeded the Josephine water level by 43 cm, and extreme water level conditions lasted for 64 hours, more than twice as long as during Josephine. Peak wave height during Frances was 4.09 m and extreme wave heights lasted for 73 hours. Figure 15 is a time series plot of water level, WLSD, and the product of water level and WLSD. High values for the product of WLSD and water level indicate periods of high waves coincident with high-water levels. TS Josephine and Frances are prominent peaks in this plot. Also very evident in the plot are the quiescent conditions that existed during 1994 and 1997.

Discussion

The water level and wave conditions that occurred during TS Josephine appear to be the threshold when significant dune and beach changes occur along the upper Texas coast. The mean higher high water level (MHHW) approximates the elevation of the top of the beach berm. Adding half of the height of the waves to the water level heights relative to MHHW indicates the reach of the storm waves above the pre-storm berm. For Josephine, this elevation peaked at 2.27 m and heights above 2.0 m lasted for about 11 hours.

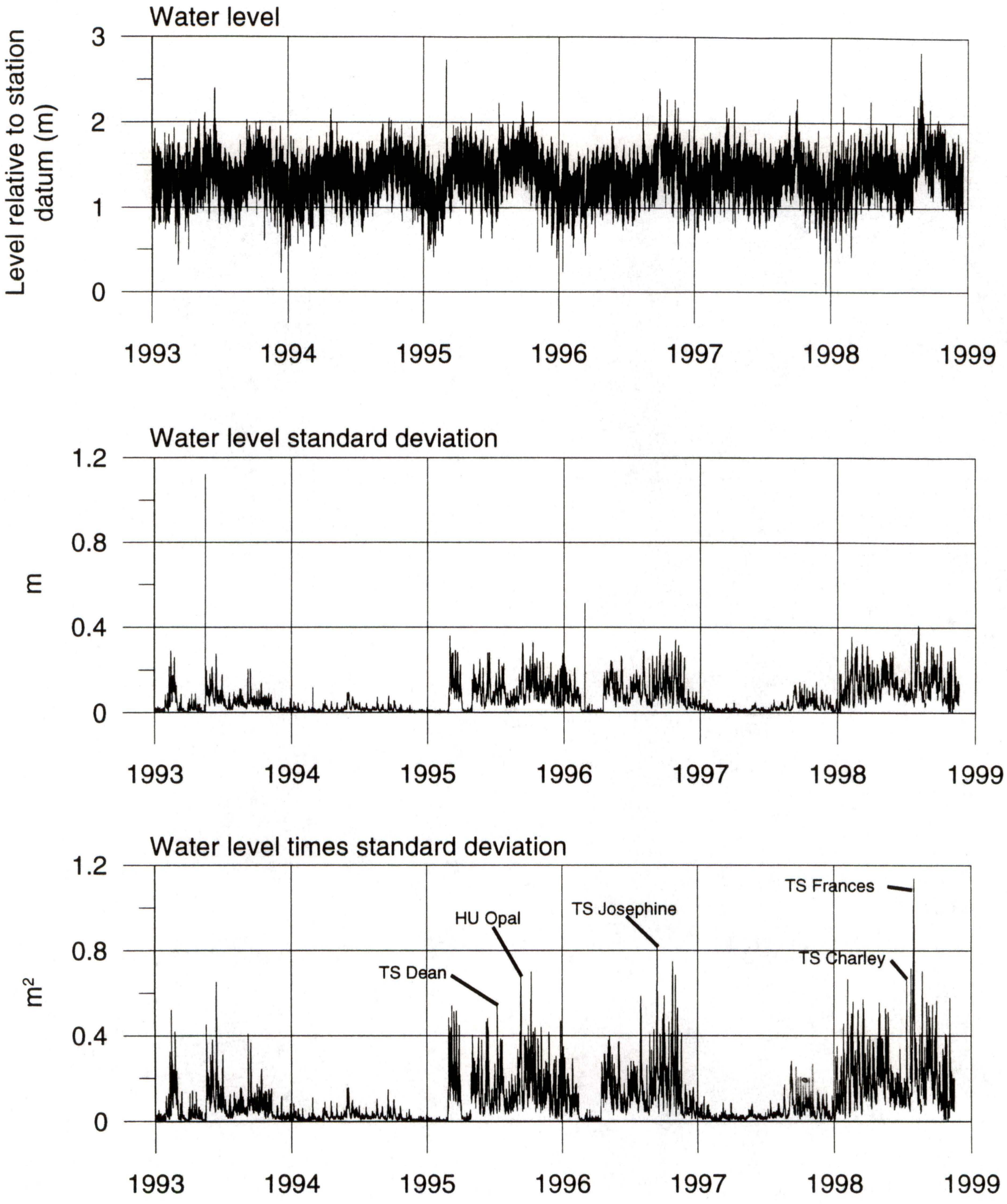


Figure 15. Water level, water level standard deviation (WLSD) and the product of water level and water level standard deviation for the period 1993 through September 1998. Data recorded hourly at the Pleasure Pier tide gauge, see figure 5 for location.

This allowed the cutting back or complete erosion of incipient foredunes and vegetated, artificial sand piles formed by beach scraping. The tops of these incipient foredunes and sand piles were generally 1.5- to 2.0-m above the berm. In areas of relatively high rates of long-term shoreline retreat, such as northeast of San Luis Pass at GLO-01, southwest of the Galveston seawall at GLO-08, BEG-01, and GLO-09, and adjacent to Rollover Pass at GLO-20, 21, and 22, scarps were reactivated by Josephine. At all other locations only the incipient dunes were cut back and the landward primary dunes that were 2.5- to 3.5-m above the berm top were not affected.

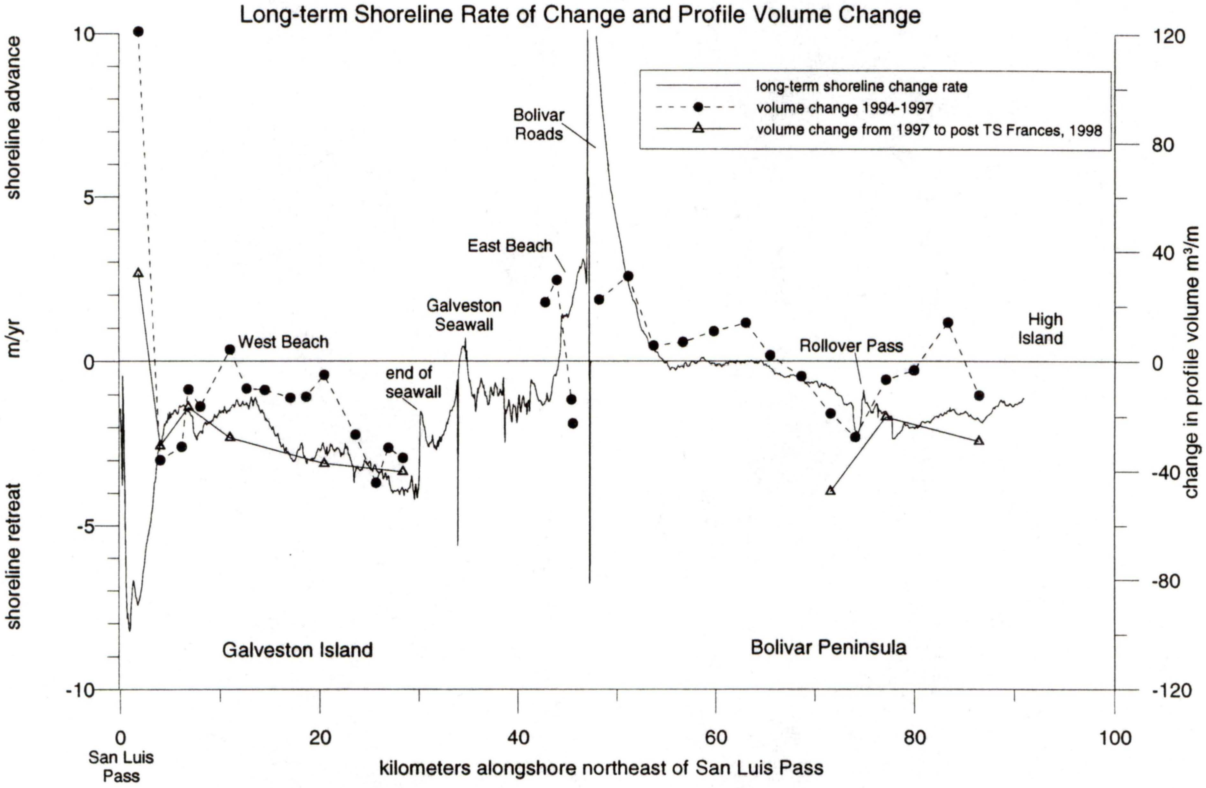


Figure 16. Comparison of long-term shoreline change and profile volume change caused by Tropical Storms Josephine (September 1994 to November 1997) and Frances (November 1997 to September 1998).

TS Frances had a much greater impact on the beaches and dunes than TS Josephine. The upper reach of the storm waves, computed as above, was 3.0-m above the berm tops and heights greater than 2.0 m lasted 53 hours. This caused extensive scarp retreat in the same areas as Josephine, but it also completely eroded the primary foredunes along much of

West Beach as displayed in the BEG-02 profiles. At BEG-02, the primary foredune was about 2.7-m above the berm top, and the vegetated dune system was 26-m wide. In the area of relatively low long-term shoreline retreat rates along Galveston Island's West Beach (11- to 14-km northeast of San Luis Pass, Fig. 16), the incipient foredunes eroded completely but the primary foredunes survived. The primary foredunes in this area are 3.0- to 3.5- m above the berm tops, and the vegetated dune system was 58-m wide before Frances.

The variable heights and widths of the foredunes along this coast made a significant difference in the type of erosion and effects on landward property caused by TS Frances. Where foredunes were less than 3-m above the berm tops and narrower than 30 m, they were completely eroded and overwash occurred. Foredunes higher than 3 m and wider than 30 m protected the landward environment. A future storm with waves reaching just 0.5 m higher than during Frances could cause complete removal of foredunes along all of West Beach.

Overall, TS Josephine caused the greatest change during the storm and for at least one year after the storm where the shoreline is experiencing relatively high rates of long-term retreat (Fig. 16). This correlation is explained by low dunes, no dunes, or the presence of scarps when the storm struck and by a lack of sand for recovery during the year after the storm in areas of high long-term shoreline retreat. The northeast side of San Luis Pass at profile BEG-04 is a notable exception. Long-term shoreline retreat rates here are the highest on Galveston Island, but the beach and foredune grew tremendously from 1994 to 1997. The TABS buoy B (Fig. 5) shows surface currents during Josephine were directed toward the southwest and peaked at over 100 cm/s. This alongshore current indicates that sand eroded during Josephine was transported to the southwest and that some of this sand was added to the beaches at BEG-04. Beaches near San Luis Pass are dynamic because they are affected by shifting tidal channels and shoals. Therefore, it is not expected that the accretion at BEG-04 will continue in the long-term (5+ years).

Conclusions

1. Of the eight tropical storms and hurricanes affecting the northwestern Gulf of Mexico from 1994 to 1998, only Tropical Storm's Josephine in October 1996 and Frances in September 1998 caused significant changes in the dunes and beaches of the upper Texas coast.

2. Conditions generated by TS Josephine appear to have just exceeded the threshold above which significant episodic erosion occurs along the upper Texas coast, particularly in areas with high long-term shoreline erosion rates. Based on the Josephine conditions and other storms that did not cause significant erosion, it is estimated that the threshold conditions are open-coast water levels, as recorded by the Pleasure Pier tide gauge, that exceed 0.9 m above sea level and coincident wave heights that exceed 3 m for at least 12 hours, as recorded by the offshore NDBC buoy #42035. Lower threshold conditions will apply if the beaches and dunes have not fully recovered from a previous storm.

3. TS Frances caused significantly more erosion than TS Josephine. Vegetation line retreat caused by Josephine was 5 to 15 m along West Beach and for Frances it was 15 to 25 m. Frances also completely eroded foredunes that rose 2.5-m above the berm tops and caused overwash whereas Josephine only removed or cut back 1.5- to 2-m high incipient dunes and sand piles.

4. Preliminary data show that TS Frances did not erode and washover dunes that were more than 3-m above the berm tops or where the dune system was more than about 40-m wide. These areas are on the west end of Bolivar Peninsula, and an area on West Beach 11 to 14 km northeast of San Luis Pass where long-term shoreline retreat rates are relatively low. Additional data will be collected in 1999 to define better the effects of TS Frances.

5. TS Josephine was 500 km south of Galveston Bay when peak water levels and wave heights occurred early on October 6, 1996 (Fig. 2). Maximum wind speed at this time was only 30 kts. Coastal residents and managers should note that such a weak and

distally tracking storm can cause significant beach and dune changes and concomitant property damage and management issues.

6. Real-time data on water level and wave heights are available for the Galveston area, and emergency responders could monitor these data during a storm and get an indication of the damage to expect. Officials should also be aware of the present conditions of the beach and dune system along the coast in order to anticipate the effects of the next storm.

PLANS FOR YEAR 3

1. We will continue analysis and conduct field experiments on the effect of vegetation on ALTM surveys, particularly on the effect vegetation has on dune sand volume and morphology measurements.

2. Foredune volume will be calculated along the southeast Texas coast using the LIDAR survey. This work will establish a general procedure that others may follow for this type of calculation.

3. The shoreline will be mapped along the southeast Texas coast using multiple LIDAR surveys in conjunction with beach profile measurements. This work will establish a general procedure that others may follow for this type of mapping. We will also compute the rate of shoreline change through comparison with earlier shorelines.

4. Weather and wave data will continue to be compiled and analyzed.

5. Wave refraction analysis will continue for the southeast Texas coast.

6. Integration of LIDAR DEM's with other remote sensing data such as digital orthophotos, airborne multispectral, and airborne synthetic aperture radar data will continue.

7. Our next survey of the southeast Texas coast is tentatively scheduled for April/May 2000. This survey will include LIDAR and ground beach profile measurements.

APPENDIX A

Abstract from 1999 AAPG Meeting

Gibeaut, J. C., Gutierrez, R., Smyth, R. C., Crawford, M. M., Slatton, K. C., and Neuenschwander, A. L., 1999, Mapping topography and bathymetry of barrier islands using airborne, terrestrial, and marine systems: American Association of Petroleum Geologists Annual Convention Official Program, v. 8.

The shapes and elevations of barrier islands can change dramatically during a storm. And between storms sediment is constantly shifting to and from these islands and among various depositional subenvironments. To investigate these changes coastal geologists have had to either settle for regional studies with sparse topographic data or small-area studies with more detailed data. With the advent of the Global Positioning System (GPS) and its incorporation into air, land, and sea surveying systems we are now able to map 10's of kilometers of coast in a day with unprecedented accuracy and detail.

We are applying the following four topographic/bathymetric surveying methods to monitor 150 km of the upper Texas coast: (1) airborne laser altimeter surveys of the backbarrier, foredune, and upper beach with 15 cm accuracy and 2 m data spacing, (2) vehicular kinematic GPS surveys of the upper and lower beach with horizontal and vertical accuracy of 2 cm, (3) electronic total station surveys of selected transects from landward of the foredune into the surf zone, and (4) nearshore GPS/echosounder surveys with 6-cm accuracy extending selected transects to approximately 7-m water depth. We are also experimenting with interferometric airborne synthetic aperture radar to rapidly acquire regional topographic coverage in the low-relief coastal zone. These topographic data allow us to develop a sediment budget for an entire barrier island system. We are also using the detailed topography to aid the interpretation and classification of optical and radar remote sensing imagery.

APPENDIX B

Abstract from 1999 Fall AGU Meeting

Gutierrez, R., Gibeaut, J. C., Gutelius, W., and MacPherson, E., 1999, Characterization of coastal change using airborne LIDAR mapping: Supplement to Eos Transactions, AGU Vol. 80, No. 46, p. F437.

Since 1997 the University of Texas at Austin and Optech, Inc. have flown airborne LIDAR over portions of the northern Texas Gulf coast. A series of digital elevation models (DEM) were generated using LIDAR data of Bolivar Peninsula, a 45 km long barrier landform at the mouth of Galveston Bay. To remove LIDAR elevation biases, LIDAR elevations were adjusted to conform with ground control, including road surveys and beach profiles. LIDAR ellipsoid heights were transformed into orthometric heights using the National Geodetic Survey G96sss geoid model and adjusted to local mean sea level using GPS ties to the Port Bolivar tide gauge. Spatial filtering was done in an attempt to discriminate LIDAR returns from vegetation from the terrain surface. As a result, a pair of 5m x 5m DEM show the elevation of the terrain-only surface and the vegetation-terrain surface for the entire peninsula. During 10-11 September, 1998 Tropical Storm Francis came ashore on the northern Texas coast. LIDAR mapping done between November, 1997 and September, 1998 document the effects of Francis on Bolivar Peninsula. A series of 2m x 2m DEM of the Bolivar shoreline were generated to study the effects of Francis. Using these higher-resolution DEM we quantified coastal change in terms of shoreline retreat, beach and dune erosion, and volume of sand loss.