Threshold Conditions for Episodic Beach Erosion along the Southeast Texas Coast

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Abstract

Changes in beach and dune topography along the Gulf of Mexico shoreline in Galveston County, Texas, were documented by comparing beach profiles measured from 1994 through 1998. During this time, although eight tropical storms and hurricanes affected the northwestern Gulf of Mexico, only Tropical Storms Josephine in October 1996 and Frances in September 1998 caused significant changes in the dunes and beaches of the southeast Texas coast.

Conditions generated by Josephine appear to have just exceeded the threshold above which significant episodic erosion occurs, resulting in dune erosion, overwash, and damage to structures. It is estimated that the threshold conditions are ocean levels that exceed 0.9 m above sea level and coincident wave heights that exceed 3 m for at least 12 hours. The amount of episodic change caused by Josephine and Frances at a particular location is related to the dimensions and shapes of beaches and dunes, which are partly controlled by relic geomorphic features and rate of long-term (50 yr) shoreline change.

During Frances, ocean level exceeded 1 m above sea level, with coincident wave heights greater than 2.3 m for 60 hours. Frances, however, did not completely erode or wash over dunes that were more than 3 m above the beach berm tops or where the dune system was more than about 30 m wide. Comparisons of water levels, wave heights, beach morphology and dimensions, and resulting erosion are providing a basis for devising a storm-susceptibility classification.

Introduction

Storm surge generated by hurricanes impacting the southeast Texas coast can completely inundate the low-lying sandy barrier islands and peninsulas. These storms transport large amounts of sediment and may destroy houses and infrastructure far landward from the beach. Long-term shoreline retreat and increasing development, however, have increased the significance of the impacts of lesser storms that cause episodic beach and dune erosion but not necessarily massive wind and storm surge destruction. During the passage of Tropical Storm Josephine in October 1996, the dunes and beaches along the Gulf of Mexico shoreline of Galveston County, Texas, eroded and put many beachfront structures at risk of failure. In September 1998, Tropical Storm Frances caused even greater erosion of the beach/dune system and undermining of structures. Both of these storms were followed by emergency erosion control efforts in the form of hay bales after Josephine, sand-filled geotextile tubes installed following Frances, and small beach nourishment projects to shore up houses. These significant efforts followed tropical storms with less than one-third the storm surge heights of a 100-year storm. Furthermore, other cyclones traversing the northern Gulf of Mexico had no episodic effect on beaches and dunes. This paper examines the alongshore patterns and amounts of episodic beach/dune change (or no change) from 1994 to 1998. The goal is to determine the threshold conditions above which we can expect significant erosion and hence undermining of beachfront structures during a particular storm and at a particular location.

Physical Setting

The southeastern shore of Texas is a microtidal, wave-dominated coast in the classification of Hayes (1979). Tides are chiefly diurnal with a diurnal range of 0.65 m as measured at the open-ocean Galveston Pleasure Pier tide gauge (Fig. 1). Mean significant wave height (Hs), as determined from 20 years of hindcast data, is 1.2 m with a mean peak wave period (Tp) of 5.8 s (Hubertz and Brooks, 1989, station number 12). The hindcast study did not include waves generated by tropical cyclones. The study area, however, is greatly affected by both tropical storms (TS) and hurricanes. Tide records from the bay side of Galveston Island show that storm surges exceeded 1.2 m about every 5 years from 1908 to 1983 (Morton and Paine, 1985). In a hurricane hindcast study that included storms occurring from 1956 to 1975, the return interval for a Hs of 6.2 m was determined to be 5 years (Abel et al., 1989, station number 12). Hurricane Alicia, in 1983, was the most recent hurricane to strike the southeast Texas coast. Alicia was a minimal category 3 storm (Garcia and Flor, 1984) and crossed the coast at San Luis Pass (Fig. 1), causing extensive property damage and beach and dune erosion along Galveston and Follets Islands (Morton and Paine, 1985; Morton et al., 1994).

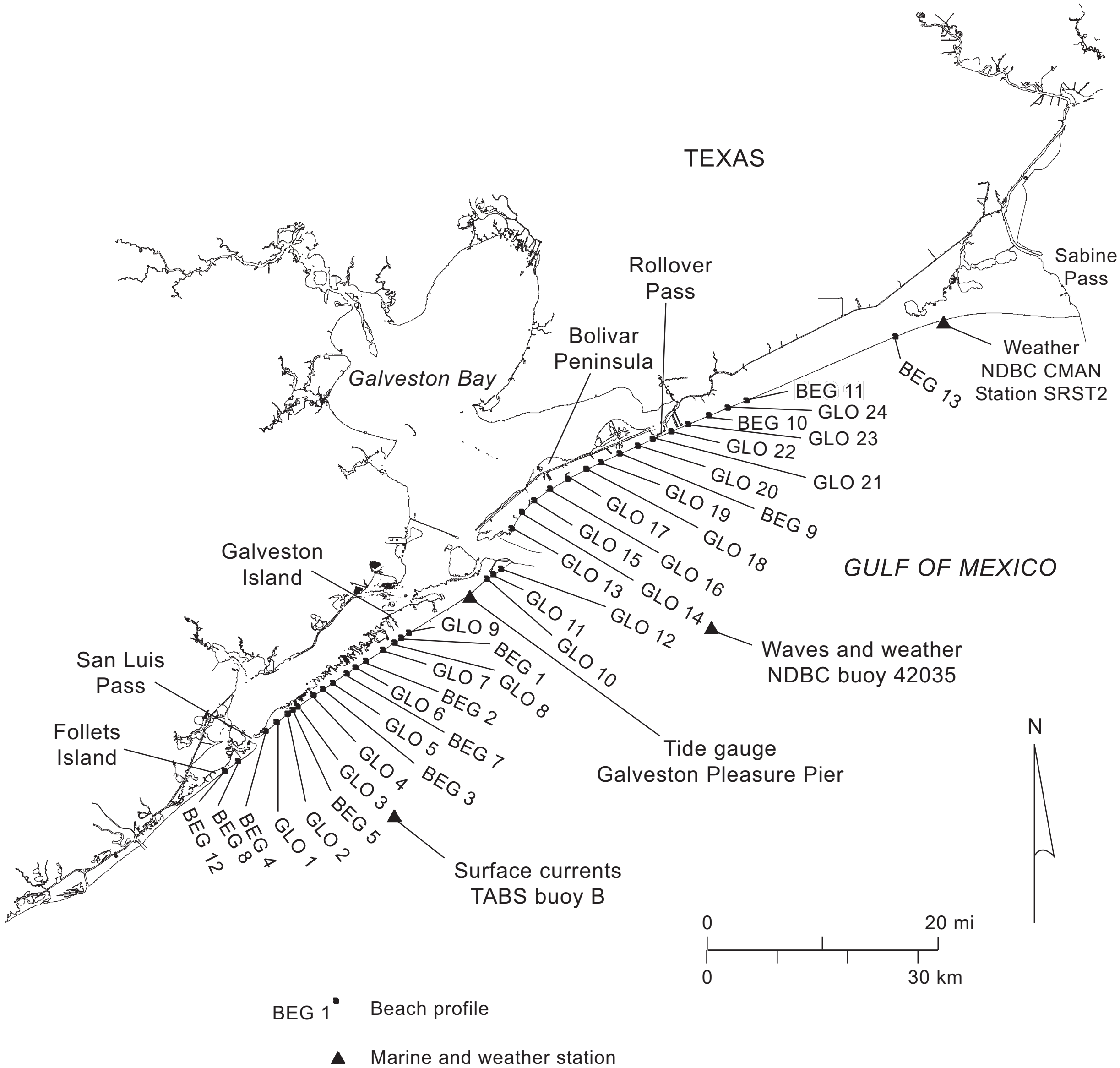

Figure 1. Map of the southeast Texas coast showing beach profile and oceanographic and meteorological stations. The NDBC CMAN station is a coastal weather station located at Sea Rim State Park and operated by the National Data Buoy Center. The station provides hourly wind direction and speed data as well as other standard weather measurements. The NDBC buoy records weather observations and non-directional wave data. The Blucher Institute of Texas A&M University at Corpus Christi operates the tide gauge at the Galveston Pleasure Pier for the National Oceanic and Atmospheric Administration. This station records water levels and standard deviations of the water levels as well as 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.

Methods

In 1994 and again in 1997, we surveyed 32 beach/dune topographic transects (beach profiles) (Fig. 1). Subsets of these profiles were surveyed in 1995, 1996, and before and after TS Frances in 1998. The surveys 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. The position of the seaward edge of vegetation (vegetation line) was noted during the surveys.

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 per meter of shoreline. The upper berm crest was picked as the shoreline feature, but some profiles had no discernible berm. 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 was for profiles without berm crests.

Data on waves, water level, and wind were acquired for the period from 1994 to 1998 or for only 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 1. Tropical storm and hurricane tracks and wind velocities were obtained from the National Hurricane Center (Figs. 2 and 3). Data were compared to changes in the beach profiles.

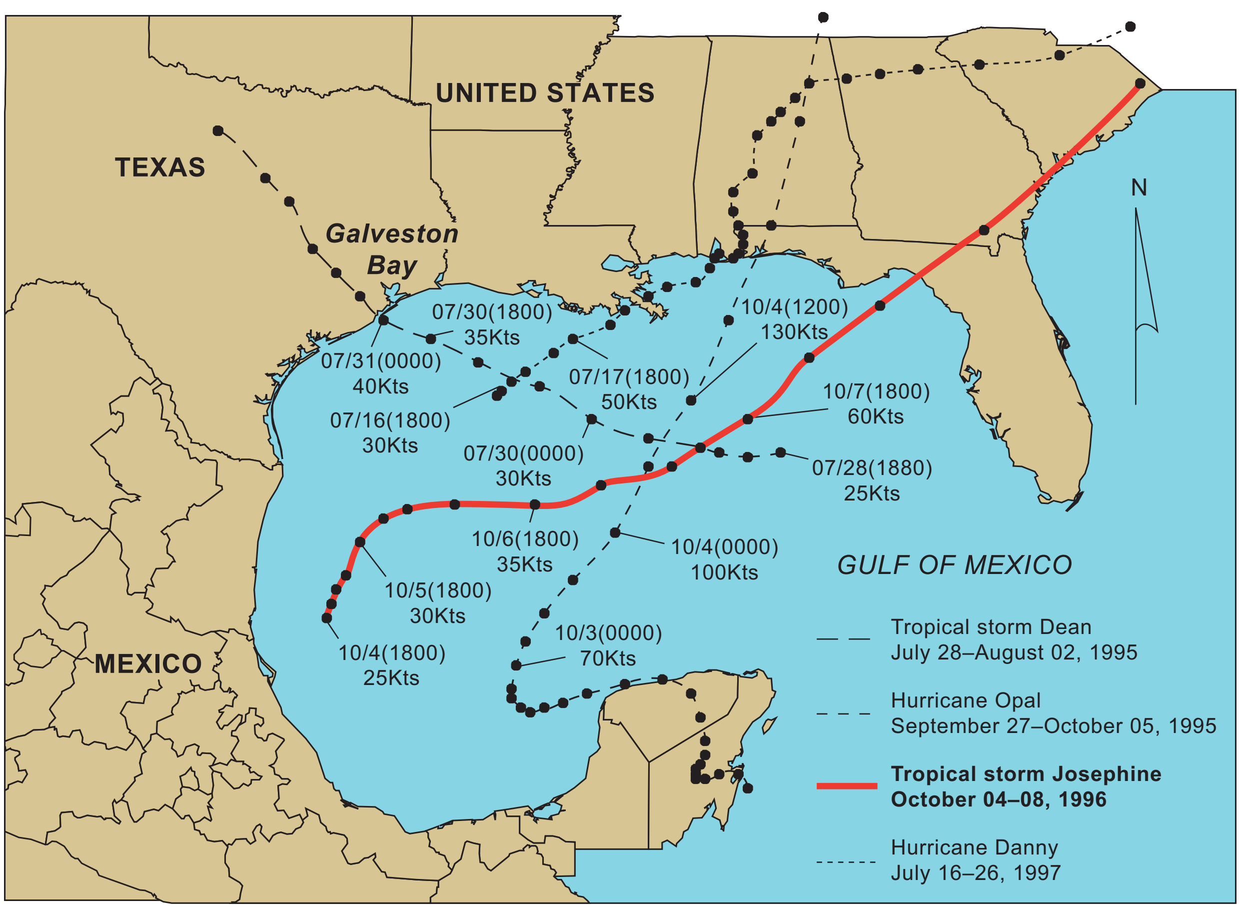

Figure 2. Wind speeds and tracks of tropical storms and hurricanes that affected the northwestern Gulf of Mexico from 1994 to 1997. No storms occurred in 1994.

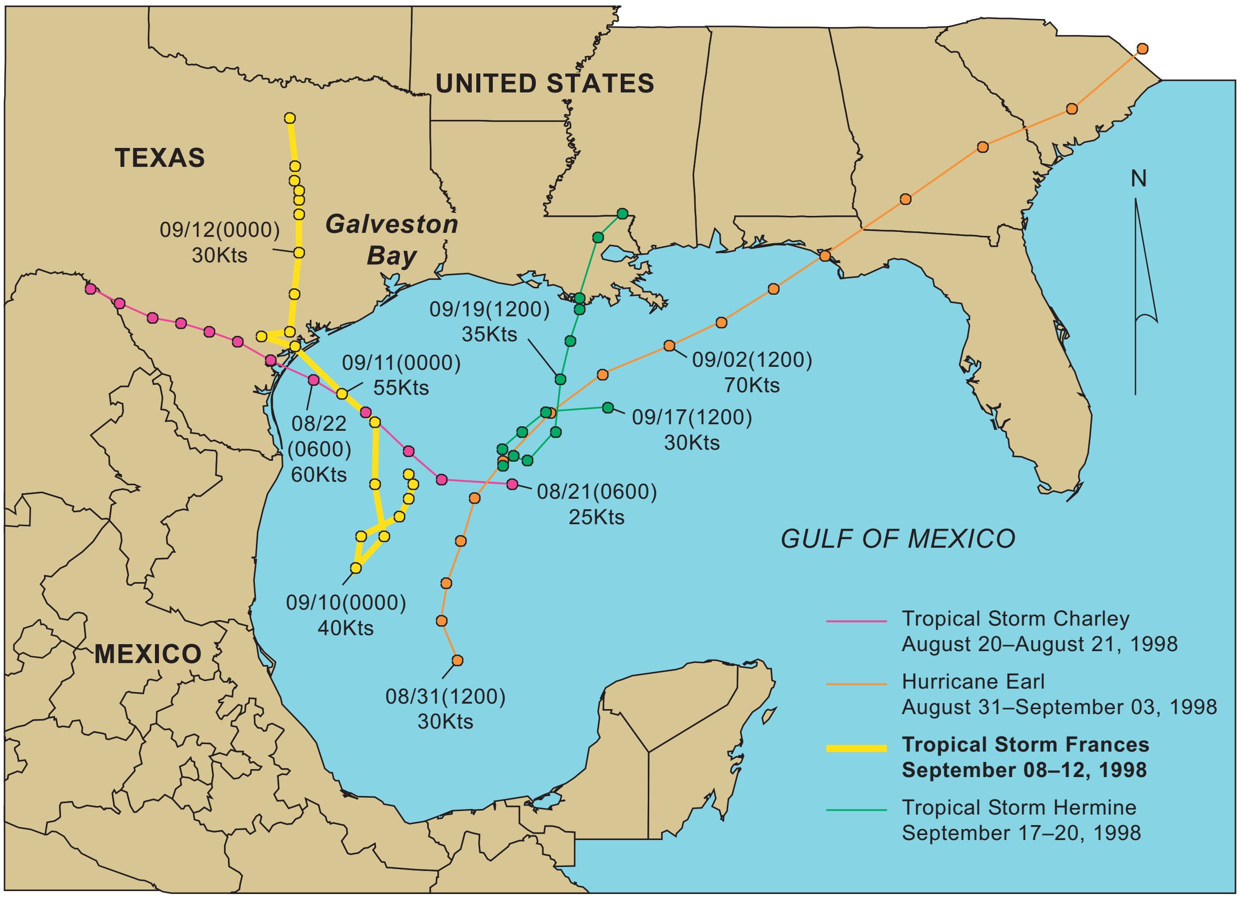

Figure 3. Wind speeds and tracks of tropical storms and hurricanes that affected the northwestern Gulf of Mexico in 1998.

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Results

Beach Profiles, 1994 to 1997

A comparison of the 1994 and 1997 beach profiles shows alongshore variation in the movement of the vegetation line and shoreline, and in sand volume (Fig. 4). Along East Beach on Galveston Island, western Bolivar Peninsula, and east of Rollover Pass, the vegetation line was relatively stable (Fig. 4a). However, the vegetation line retreated 5 to 15 m in areas southwest of San Luis Pass, along West Beach on Galveston Island, and near Rollover Pass. Consideration of beach profiles measured in 1995 and 1996 and field observations show that the vegetation line retreat was episodic and caused by TS Josephine in October of 1996. Along West Beach, vegetation line retreat was relatively high next to the southwest end of the Galveston Seawall and less in an area 11 to 15 km to the northeast of San Luis Pass (GLO-4 and BEG-3 area). Within 4 km of San Luis Pass, large shifts in the position of the vegetation line occurred. From 1 to 3 km northeast of the pass it retreated 22 m, but within a kilometer of the pass the vegetation line advanced seaward 35 m. The growth of vegetation and subsequent advance of the vegetation line near San Luis Pass is not considered episodic, but the deposition of sand that provided the platform for the vegetation was the result of TS Josephine.

Shoreline change from 1994 to 1997 (Fig. 4b) generally followed the same pattern as vegetation line change, but was more variable and probably retreated and advanced during this period at a greater frequency than can be described by these data. It is clear, however, that Josephine caused episodic retreat of up to 23 m in areas southwest of San Luis Pass, southwest of the seawall, and Rollover Pass. The central section of West Beach and the southwest portion of Bolivar Peninsula were relatively stable, and there is no evidence in the 1997 data, which was acquired 1 year after Josephine, of episodic change caused by Josephine. Dramatic shoreline advance occurred adjacent to San Luis Pass on the northeast side (BEG-4 location).

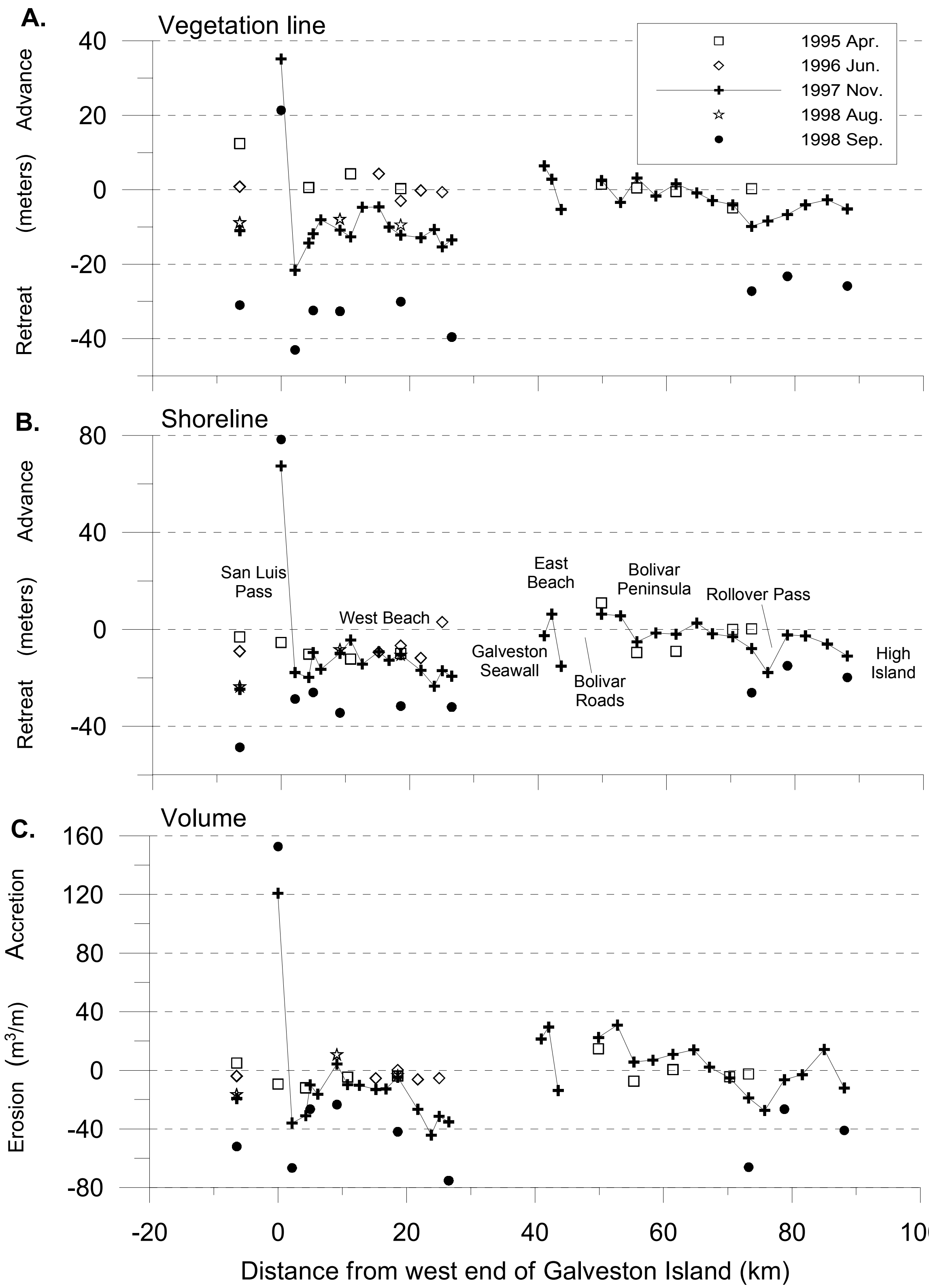

Figure 4. Cumulative change in beach profiles since September 1994: (A) vegetation line movement; (B) shoreline movement; and (C) profile volume change.

Sand volume also had generally the same pattern of change from 1994 to 1997 as the vegetation line and shoreline (Fig. 4c). The alongshore trends, however, were more pronounced. Loss of sand within 10-km southwest of the Galveston seawall exceeded 40 m^3/m. Along a 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-4 location). 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 (BEG-8), southwest of San Luis Pass, decreased in volume by 19 m^3/m. Two of the East Beach profiles increased in volume, but the easternmost 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 (Fig. 5). Erosion also either cut back or eroded completely incipient foredune deposits and coppice mounds (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-4), 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-4 and BEG-3, the 1994 berm was eroded and the shoreline moved landward, but this erosion was offset by foredune growth landward of the 1994 vegetation line (Fig. 6). Sand eroded from the berm may have been incorporated into the expanded foredune. Scarp retreat occurred northeast of San Luis Pass at GLO-1 and southwest of the Galveston seawall at GLO-9 and BEG-1.

Along the western portion of Bolivar Peninsula from GLO-13 to BEG-9, 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-9 to Rollover Pass and just east of Rollover Pass at GLO-22, the beaches lost sand in the form of scarp retreat (Fig. 7). In 1997, back-beach scarps 1 to 1.5 m high were present.

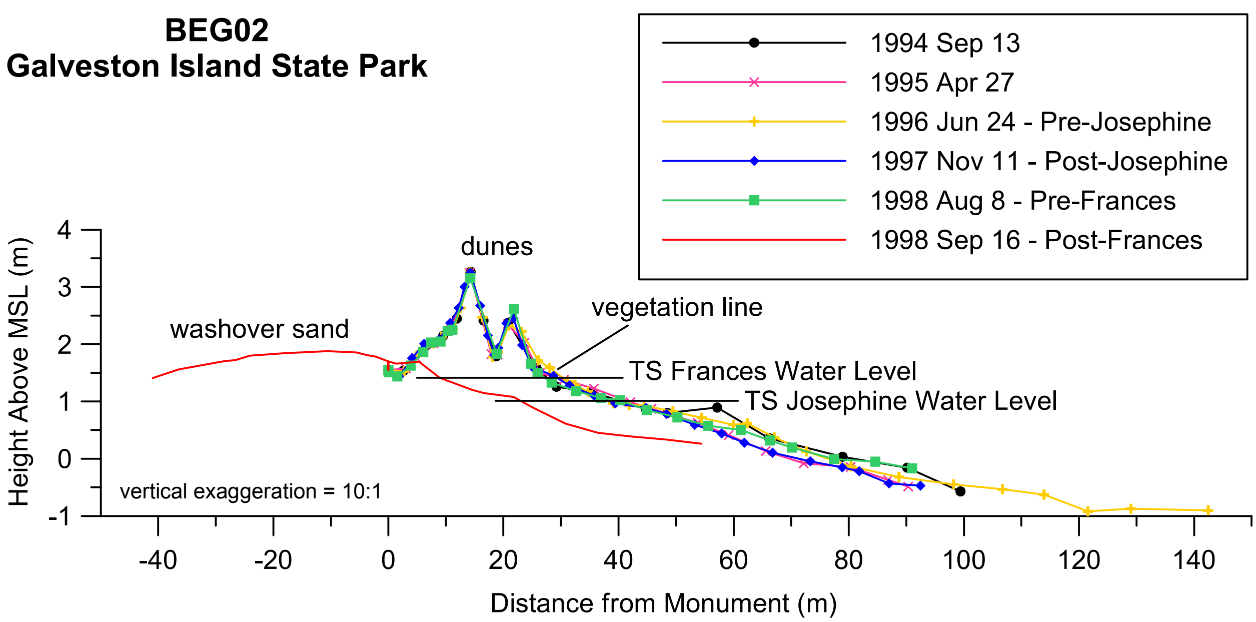

Figure 5. BEG-2 beach profile; see Figure 1 for location.

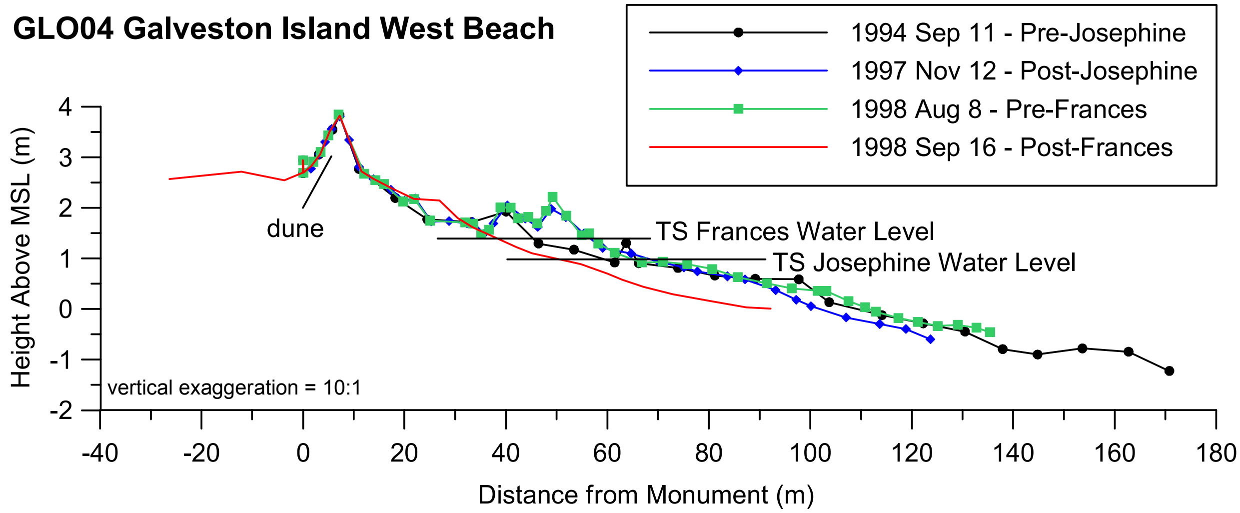

Figure 6. GLO-4 beach profile; see Figure 1 for location.

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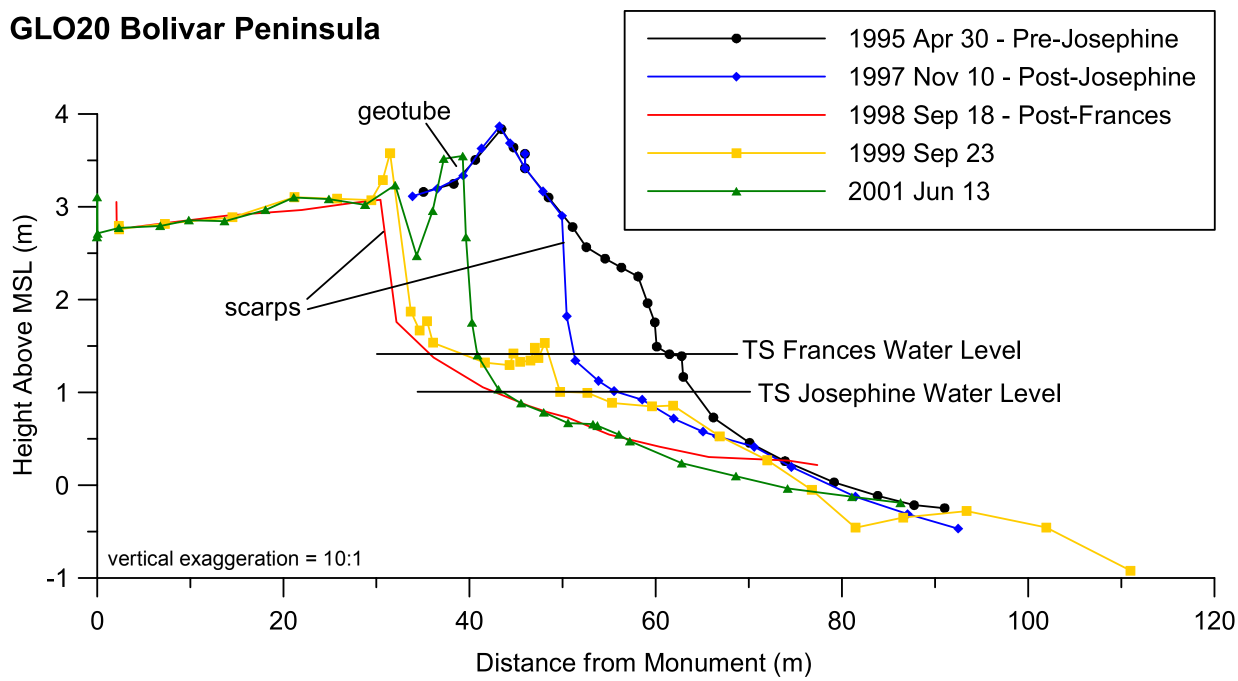

Figure 7. GLO-20 beach profile; see Figure 1 for location.

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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. 4a). 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 Frances had a much greater effect on the beaches than Josephine. Along West Beach from the seawall (GLO-9 location) to west of Galveston Island State Park (GLO-6 location) the foredunes were completely eroded. The foredune and incipient foredune at Galveston Island State Park (BEG-2) (Fig. 1) were flattened with a portion of the sand washed landward into the picnic area (Fig. 5). Farther to the west, in the area of GLO-4 (Fig. 1), piles of vegetated sand in front of the natural foredune were completely eroded, but the foredune survived (Fig. 6). Farther to the west at

GLO-1, a scarp that had been cut back by Josephine in 1996 retreated an additional 25 m. Next to San Luis Pass at BEG-4, the vegetation line also retreated, but the beach still had more sand than it did in 1997 (Fig. 4c). On Follets Island at BEG-8, the foredune completely eroded.

Storms from 1994 to 1998

Figures 2 and 3 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 southeastern Texas coast, but other storms had tracks just as close or closer to the study area as Josephine and Frances. Figures 8 and 9 are graphs for Josephine and Frances showing wave height and period, and wind speed and direction from NDBC buoy 42035, and water level standard deviation (WLSD) from the open-coast tide gauge at the Galveston Pleasure Pier (Fig. 1).

Water level at the tide gauge is computed by smoothing 181 1-second readings. The standard deviation of these 181 readings is 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 and may in fact be a better parameter for measuring relative wave energy arriving at the coast than data from the offshore buoy.

The key parameters of peak water level, peak WLSD, and peak wave height are presented in Table 1. 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 1 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.

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 Charley'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 probably 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. 3) 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 10 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. Upper berm elevations form at about 0.6 m above mean sea level (MSL), which corresponds to 2 m above the station datum for the Pleasure Pier tide gauge. Vegetation line retreat, dune erosion, and washover may occur when water level exceeds the upper berm level and is simultaneous with high waves. Even though storms other than Josephine and Frances caused water levels to be above berm tops, the period of elevated levels were short and did not coincide with particularly high waves. TS Josephine water levels peaked about 0.4 m above the pre-storm berm tops, allowing the high waves to cut back or completely erode 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-1, southwest of the Galveston seawall at GLO-8, BEG-1, and GLO-9, and adjacent to Rollover Pass at GLO-20, 21, and 22 (Fig. 1), scarps were reactivated by Josephine. At all other locations only the incipient dunes or coppice mounds were cut back and the landward primary dunes that were 2.5 to 3.5 m above the berm tops were not affected.

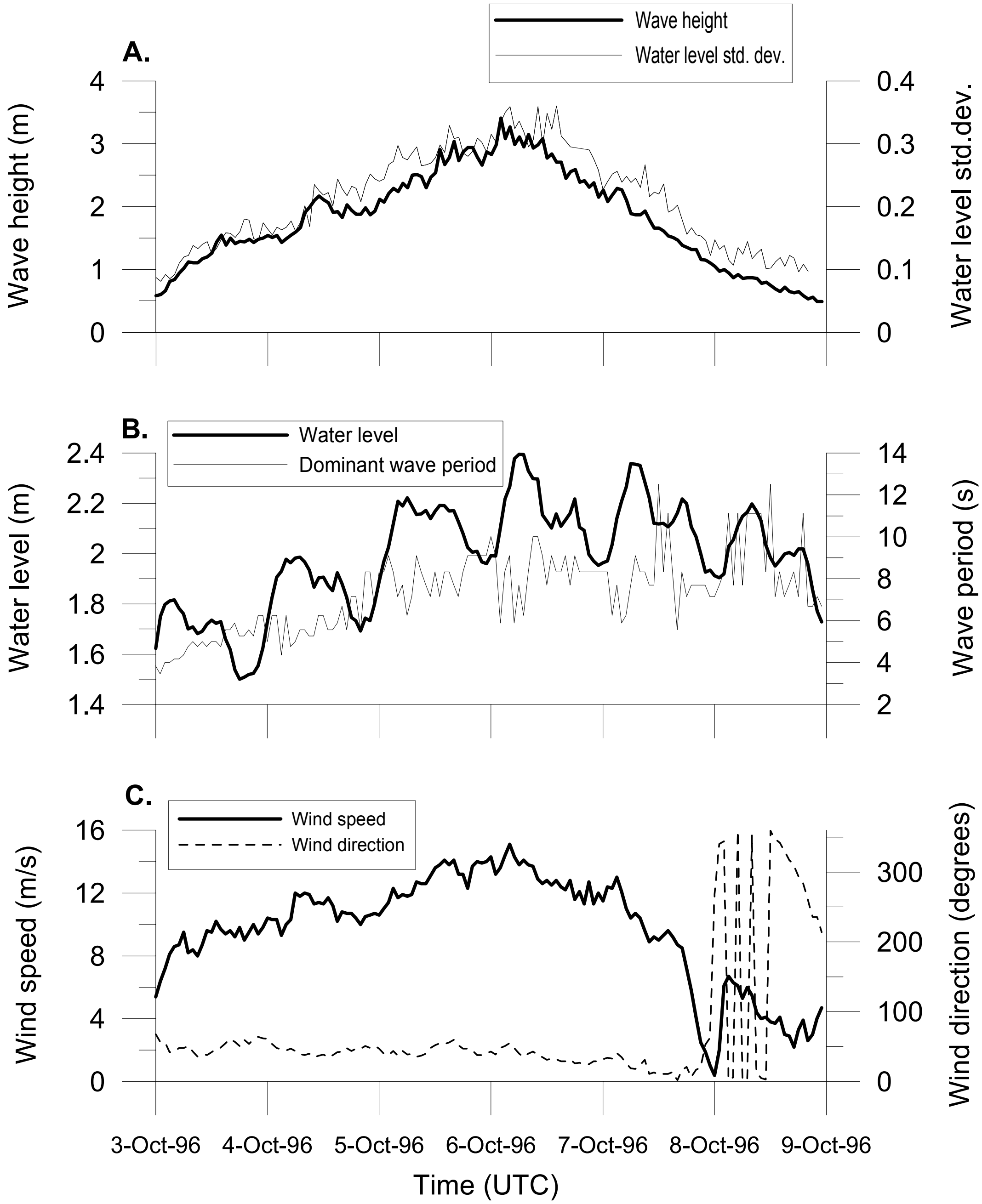

Figure 8. Comparisons of wind, water level, and wave properties during Tropical Storm Josephine. Water level and water level standard deviation data are from the Pleasure Pier open-coast tide gauge. Wave and wind data are from a moored buoy operated by the National Data Buoy Center, offshore Galveston Bay. See Figure 1 for station locations.

TS Frances had a much greater impact on the beaches and dunes than did TS Josephine. Water levels peaked at about 0.8 m above the pre-storm berm crests and coincided with waves 0.5 m higher than during Josephine. These conditions lasted twice as long as during Josephine. TS Frances 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-2 profiles (Fig. 5). At BEG-2, 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 (GLO-4 and BEG-3) (Fig. 6), 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.

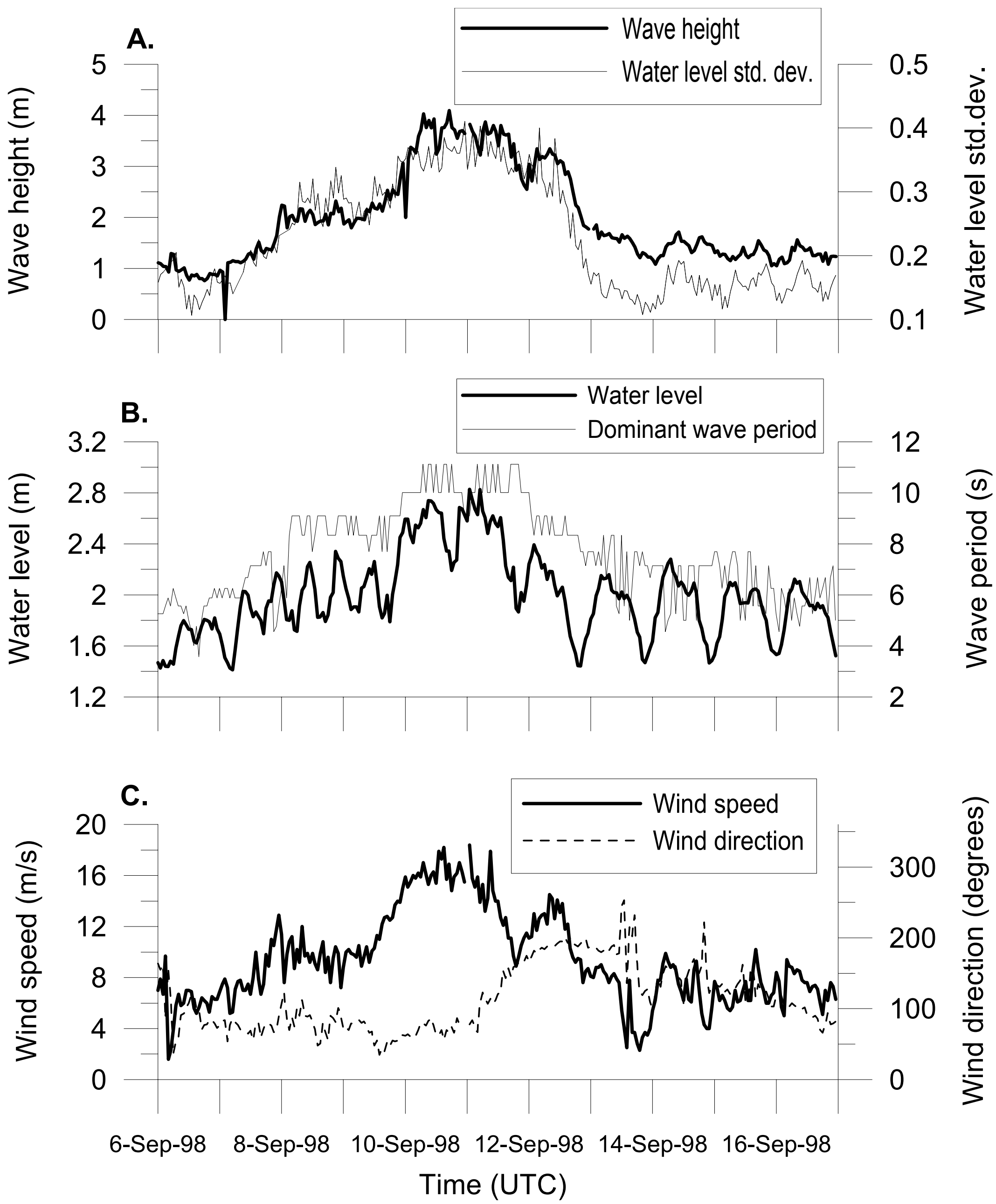

Figure 9. Comparisons of wind, water level, and wave properties during Tropical Storm Frances. Water level and water level standard deviation data are from the Pleasure Pier open-coast tide gauge. Wave and wind data are from a moored buoy operated by the National Data Buoy Center, offshore Galveston Bay. See Figure 1 for station locations.

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.

Table 1. Water levels and wave heights during tropical storms (TS) and hurricanes (HU).*

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

* 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.

Overall, TS Josephine caused the greatest change during the storm and for at least 1 year after the storm where the shoreline is experiencing relatively high rates of long-term retreat (Fig. 11). 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-4 is a notable exception. Long-term shoreline retreat rates here are the highest on Galveston Island, but the beach and fore-dune grew tremendously from 1994 to 1997. The TABS buoy B (Fig. 1) shows that 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-4. 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-4 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 Storms 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 mean 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 did. Vegetation-line retreat caused by Josephine was 5 to 15 m along West Beach, and after 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. TS Frances did not erode any 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.
5. TS Josephine was 500 km south of Galveston Bay (Fig. 2) when peak water levels and wave heights occurred early on October 6, 1996 (Fig. 8). 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.

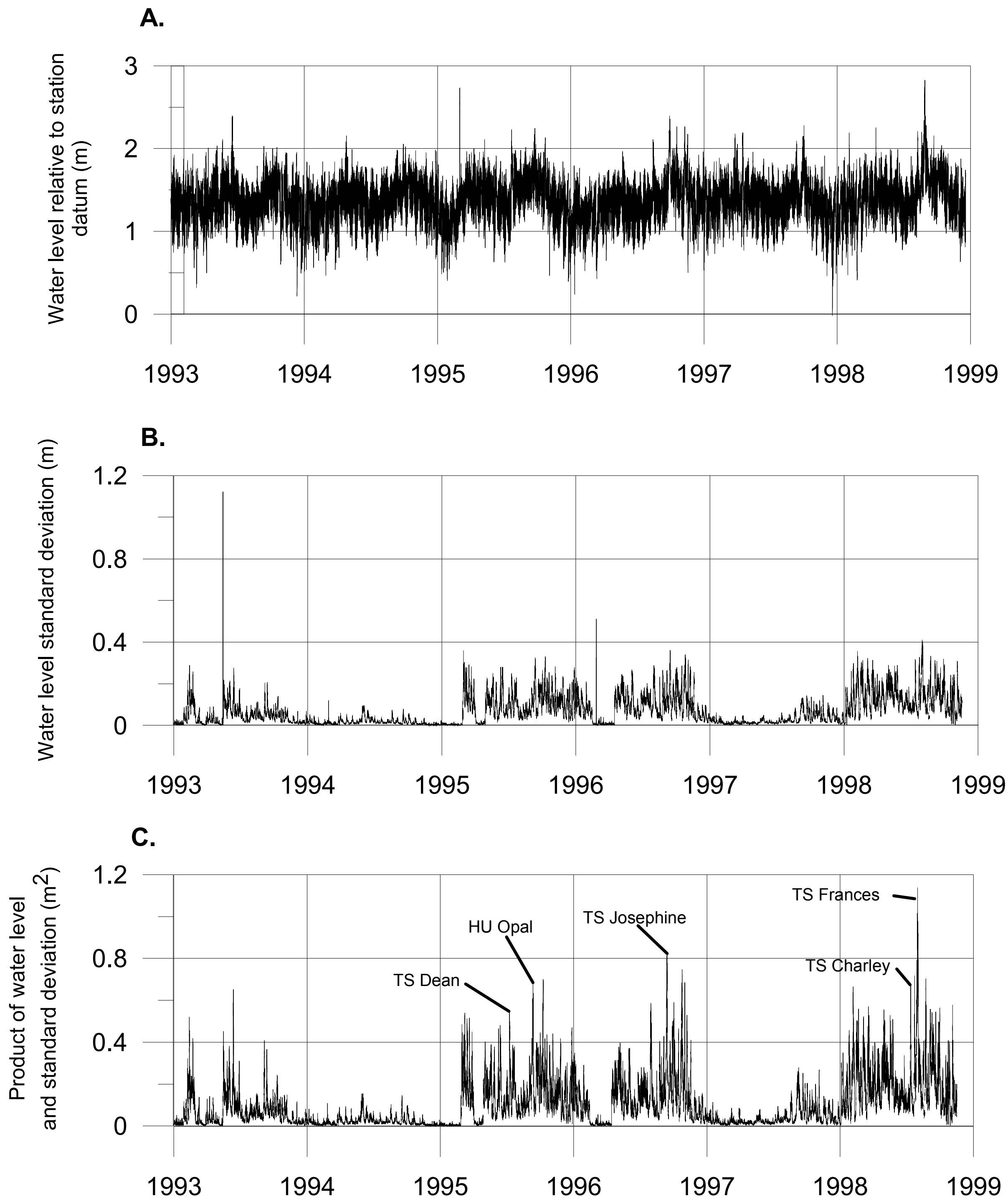

Figure 10. Water level (A), water level standard deviation (B), and the product of water level and water level standard deviation (C) for the period 1993 through September 1998. Data recorded hourly at the Pleasure Pier tide gauge. See Figure 1 for location.

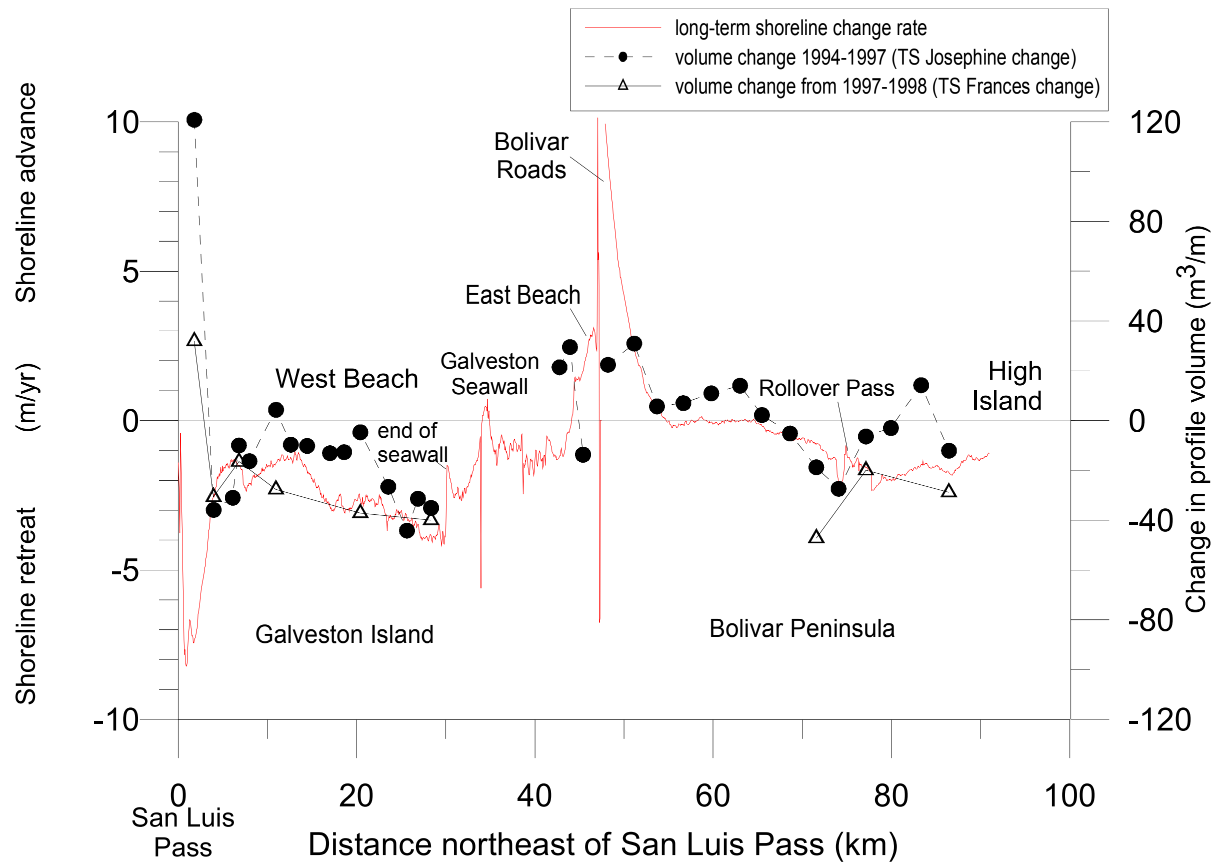

Figure 11. Comparison of long-term shoreline change and profile volume change caused by Tropical Storms Josephine (September 1994 to November 1997) and Frances (November 1997 to September 1998).

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