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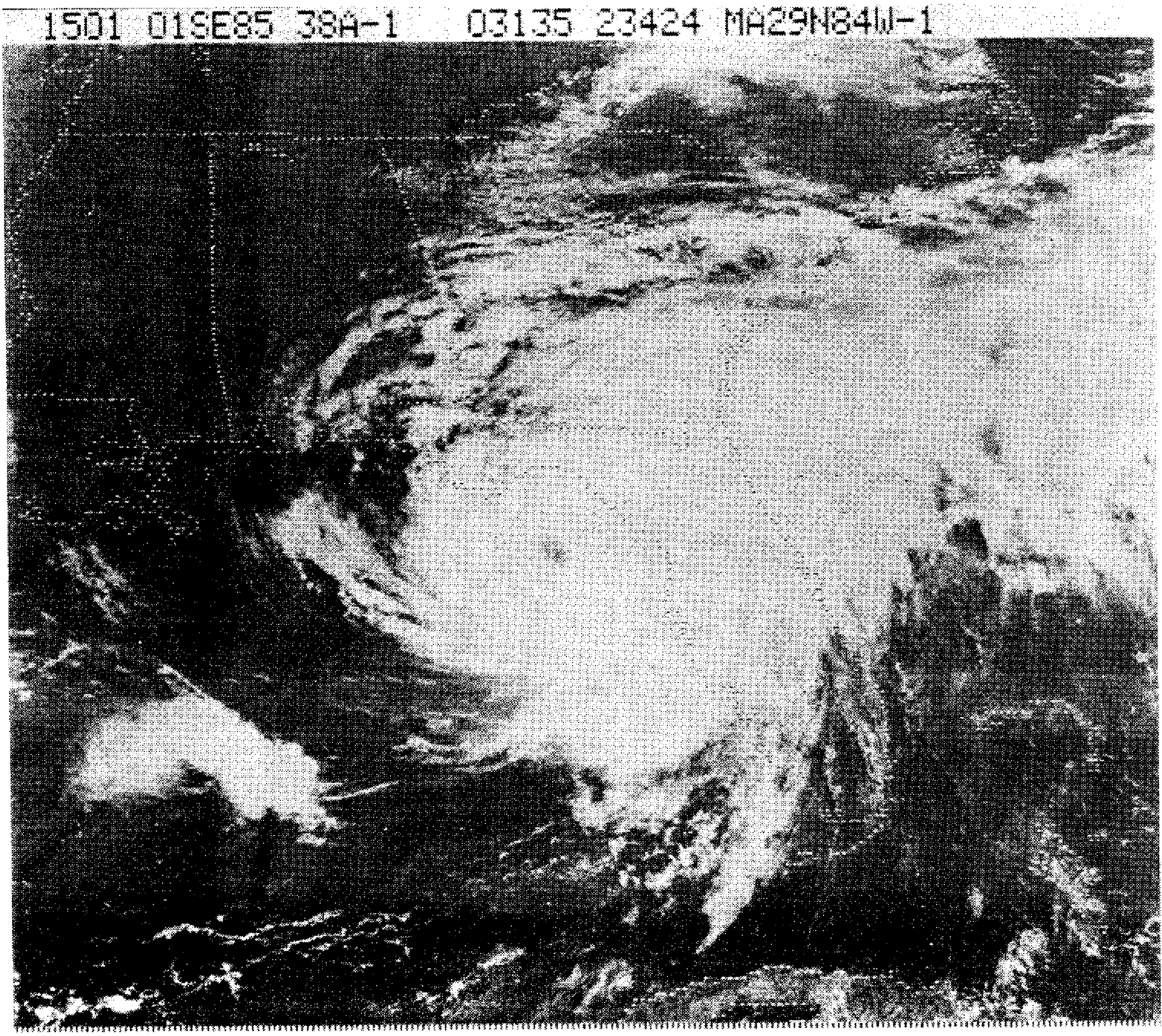
EFFECT OF HURRICANE ELENA ON FLORIDA'S MARSH-DOMINATED COAST: PASCO, HERNANDO, AND CITRUS COUNTIES



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EFFECTS OF HURRICANE ELENA ON FLORIDA'S MARSH-DOMINATED, OPEN-MARINE COASTLINE: PASCO, HERNANDO, AND CITRUS COUNTRY COAST

ABSTRACT

During late August and early September, 1985, Hurricane Elena passed erratically through the Gulf of Mexico, threatening landfall across the west-central Florida coast. This class 3 (maximum winds were 110 knots) hurricane's unusual path caused it to remain approximately stationary about 100 km off the west-central coast of Florida for 36 hours. Eventually, Elena passed off to the west-northwest making landfall along the Mississippi coast. Hurricane Elena caused the largest evacuation in U.S. history of people from coastal lowlands. This storm also caused widespread property damage and is one of the most expensive storms on record.

Hurricane Elena occurred just as a detailed geologic reconnaissance of a three country sector of Florida's open-marine, marsh-dominated coast was completed. Hurricane Elena provided an excellent opportunity to examine the effect of high energy events on this type of coast. The Pasco, Hernando, and Citrus County coast is distinctly different from the sandy barrier island coast to the south which sustained heavier damage from Elena. The marsh coast has a very low regional gradient, low wave energy, low sediment input, and is largely controlled by underlying antecedent, karstified rock topography.

Hurricane Elena had very little impact upon the natural and human structures along the marsh coast. There are several reasons for this: (1) the storm never came closer than 81 km to the west central Florida Gulf coast: (2) the dominant winds in the study area were never sustained above hurricane force (74 kts); (3) the dominant winds were alongshore/even slightly offshore; (4) the storm surge peaked at only 2m above MSL; (5) the marsh grasses absorbed wave energy and retarded erosion; (6) much of the coast has rock exposed or nearly exposed; and (7) there are relatively few people and few buildings/seawalls near the Gulf compared to the sandy coastlines.

The observed effects were: (1) some coastal erosion in the southern part of the study area (Bayonet Point, Pasco County); (2) development of small overwash fans penetrating seaward marshes; (3) flattening down of marsh grasses; (4) redistribution of small, nearshore sand bodies; (5) extensive _Juncus_ wracks in high marsh areas; and (6) breakage of dead mangroves (killed by earlier freezes).

The response of open-marine, marsh coasts to a direct strike by a major hurricane is still unknown. Storms like Hurricane Elena have a recurring frequency of 10 years. In the future, the combined effect of a greater sea-level rise with a class 5 hurricane could have much more devastating effects.

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INTRODUCTION

The purpose of this document is to assimilate the basic, physical characteristics of Hurricane Elena, which threatened the west-central coast of Florida in late August/early September of 1985, and to report on the effects that this storm had on the open-marine, marsh-dominated coastline of the Pasco, Hernando, and Citrus Counties. Several reports have already been written concerning Hurricane Elena's effect on the barrier island/barrier beach shores (Balsillie, 1985; Bodge and Kriebel, 1985), however, little has been mentioned concerning this storm's effect on the sand-starved, northern Suncoast.

Hurricane Elena appeared in the Gulf of Mexico after the authors had completed a major, detailed reconnaissance of this three county coastal sector (Hine and Belknap, 1986). As a result, we had a firm understanding concerning the major depositional processes, geomorphology, and stratigraphy prior to the arrival of Elena. This helped considerably in our assessment of the storm's impact.

BACKGROUND GEOLOGIC INFORMATION

The northwest Florida coast along the Gulf of Mexico has been recognized for some time as a unique coastal sector primarily due to its relatively low wave energy and dominance by an open-marine marsh system (Fig. 1). Indeed, many coastal scientists have viewed this area as the classic zero energy coast (Price, 1954; Tanner, 1960). Perhaps, as a result of this coastline's outwardly monotonic appearance, its unappetizing appeal to physically-oriented sedimentologists, and the strong interest in sandy, barrier island coastlines resulting from problems associated with human development the coastal geological community has looked elsewhere for questions to address. As a result, an enormous stretch of the Florida shoreline (32%), and an important type of coast have been ignored and have remained poorly understood including the effects of storms. Indeed, even to this day, the State's Bureau of Beaches and Shores, an agency charged with shoreline research, feels that this biologically-dominated coast is beyond their purview. Only as the result of a handful of studies by marsh biologists has this coastline avoided escape from scientific inquiry.

The recent geologic research along this coast has shown that the morphologic and stratigraphic complexity has resulted from a unique interaction of a suite of physical, chemical, and biological processes (Hine and Belknap, 1986).

Within just the southern 65 km, of this 300 km long non-barrier island coastal sector, four major geomorphologic subdivisions have been distinguished: (1) berm ridge shoreline, (2) marsh peninsula shoreline, (3) marsh archipelago shoreline, and (4) shelf embayment shoreline (Fig. 1). These sharply contrasting coastal zones have resulted from the interplay of five major processes/sedimentation controls: (1) antecedent topography resulting from chemical dissolution of the exposed bedrock, 2) fresh-water discharge from springs, 3) low regional gradient/low wave

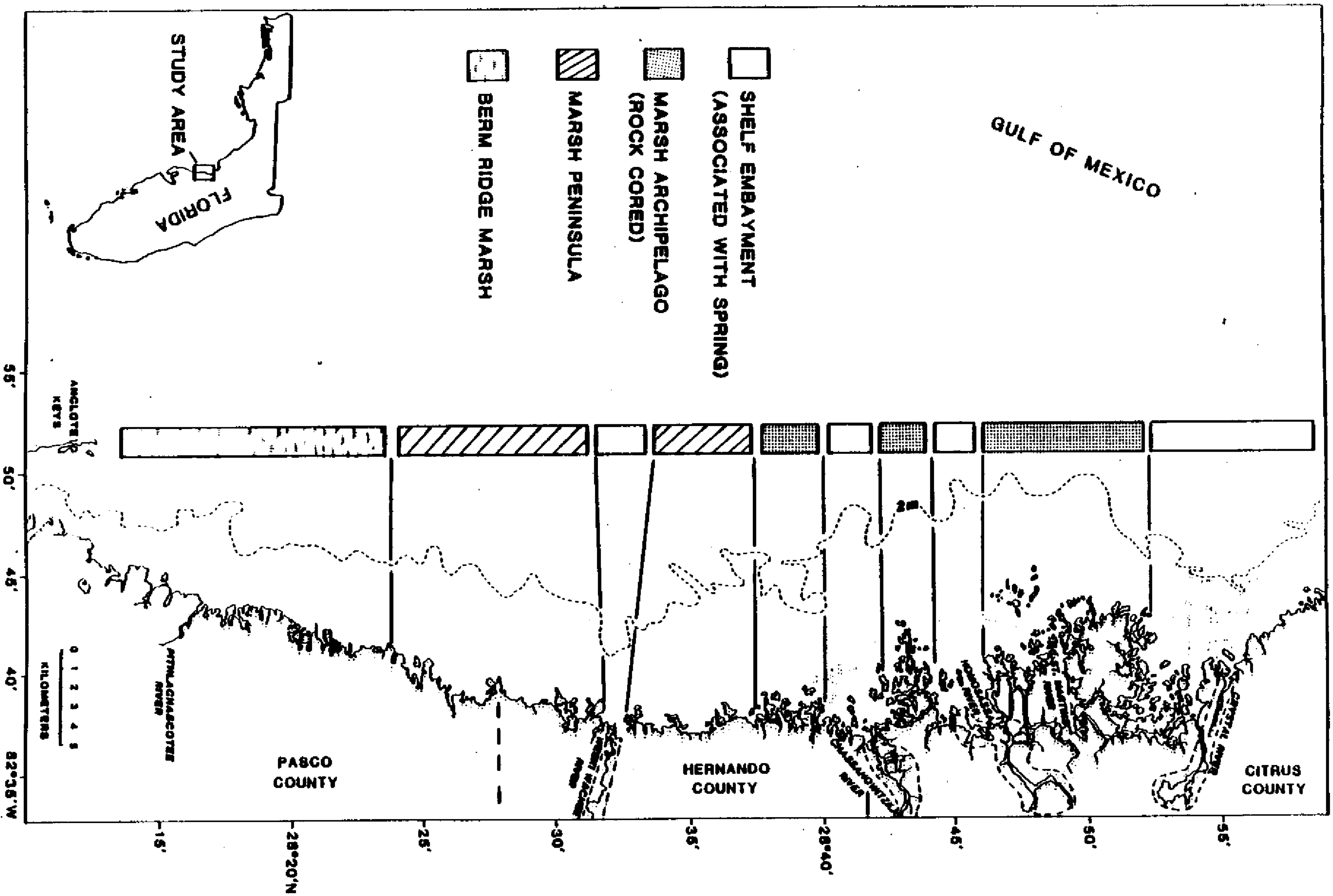


Figure 1. Location map of the Pasco, Hernando, and Citrus County marsh-dominated coastline illustrating distribution of four basic coastal morphologic sectors.

energy, (4) lack of sediment input, no relict sand supply, and (5) rising sea level. The reader is referred to Hine and Belknap (1986) for an in depth analysis of these geomorphic subdivisions. None of these subdivisions appear to have inherited or presently display effects of past hurricanes or tropical storms.

PAST HURRICANE ACTIVITY

Ho and Tracey (1975) have presented a descriptive summary of 13 hurricanes that have caused widespread damage along the Florida Gulf coast from Cape San Blas to St. Petersburg Beach from 1837 to 1972. From these data and observations, they have calculated storm surge (storm tide) frequency curves from the 500 year, 100 year, 50 year, and 10 year recurring hurricane (Fig. 2). In addition, Table 1 is a listing of tropical storms or hurricanes that have passed within 216 km (120 nm) of Crystal River. Figure 3 illustrates the tracks of some of these storms.

The storm surge is a rapid rise in normal water level due to reduced atmospheric pressure and to wind stress piling water up against an open coastline (U.S. Army Coastal Engineering Research Center, 1973). An extreme example is that of Hurricane Camille, a class 5 hurricane, which struck the northern coast of the Gulf of Mexico in 1969. The maximum elevation of the storm surge was 7.6 m (25 ft) above mean low water and that a surge greater than 3 m (9.8 ft) extended over approximately 88 km (55 mi) of coastline. Even more important, this great storm surge reached its peak in less than 5 hours-starting from a point about 75 cm (2.4 ft) below mean low water, thus rising a total of 8.35 m (27.4 ft).

The historical hurricane data for our study area does not indicate that a storm surge of similar magnitude as Hurricane Camille has occurred (Fig. 4). However, the 1842 hurricane was shown to have a storm surge of approximately 5.5 m (18 ft) at Cedar Key - a point just to the north of our field area. This 1842 storm has a predicted recurring frequency of 200 years. Figure 4 shows the tracks of two more recently occurring hurricanes (Alma, 1966; Agnes, 1972) causing storm surges at Cedar Key. Each had a storm surge of approximately 3 m (9.8 ft) and both have a recurring frequency of 26 years. Both passed offshore. Had they tracked directly over Cedar Key, the storm surges would have undoubtedly been higher. Hurricane Elena's highest measured surge along this coast was 2 m (Fig. 10) which, when plotted on the graph in Figure 4, would indicate that a storm similar to Elena would recur about every 10 years.

It is interesting to note (Fig. 5) how hurricane storm surges affect the freshwater discharge at Crystal River springs. Note that the water level curve and the spring discharge curve are negatively correlated - that is, minimum spring discharge occurs during maximum elevation of the storm surge. Maximum spring discharge occurs either before or after the storm surge during low water conditions.

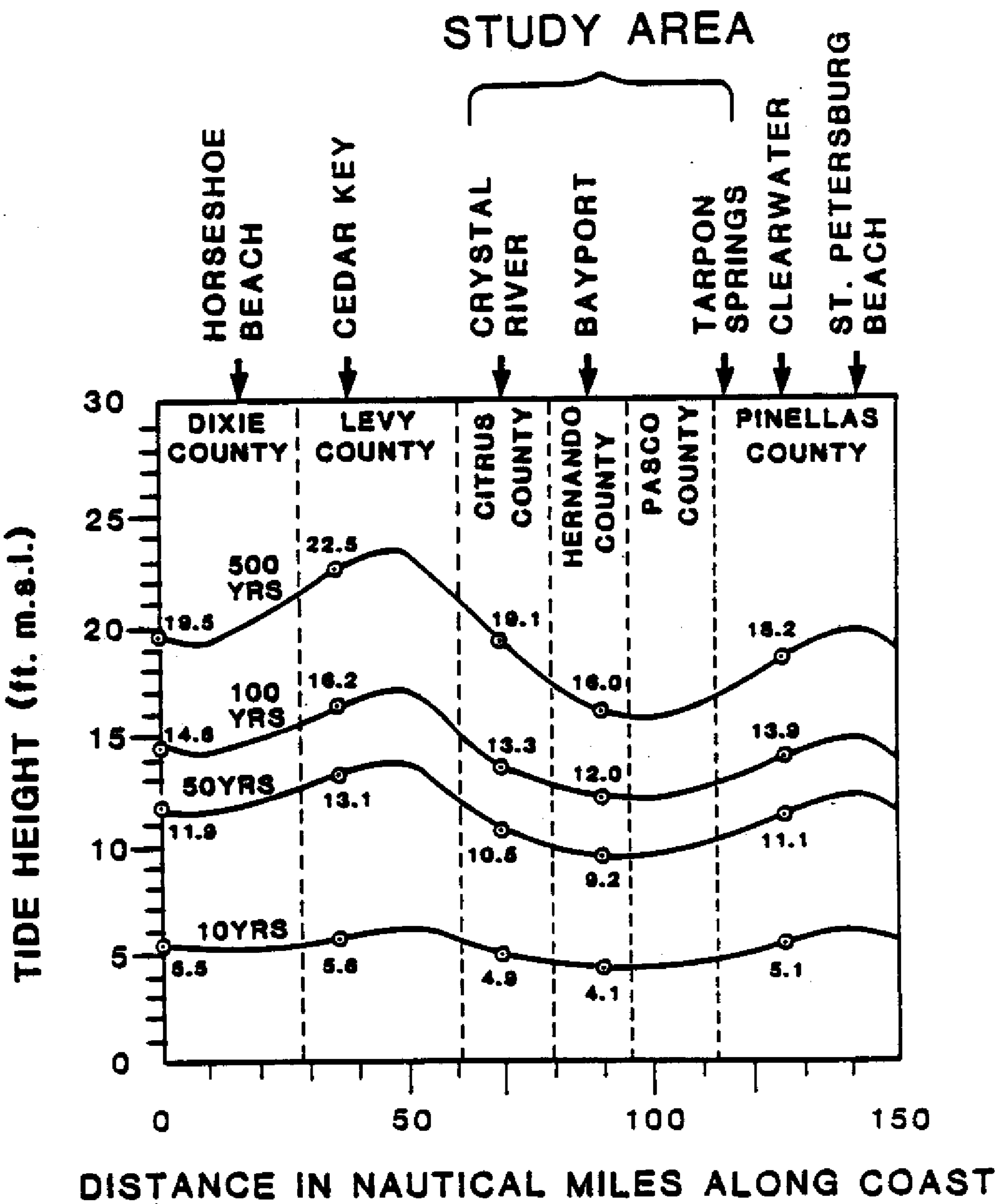


Figure 2. Calculated storm surge (storm wind tide) curves for the study area and neighboring coastline for the largest storm occurring statistically every 10, 50, 100, and 500 years (data from Ho and Tracey, 1975). With a measured storm surge of 2m at Bayport in Hernando County, the recurring frequency of such a flooding event lies between 20 and 30 years on this graph.

TABLE 1

HURRICANES PASSING WITHIN 120 NAUTICAL MILES
OF CRYSTAL RIVER: 1886-1981

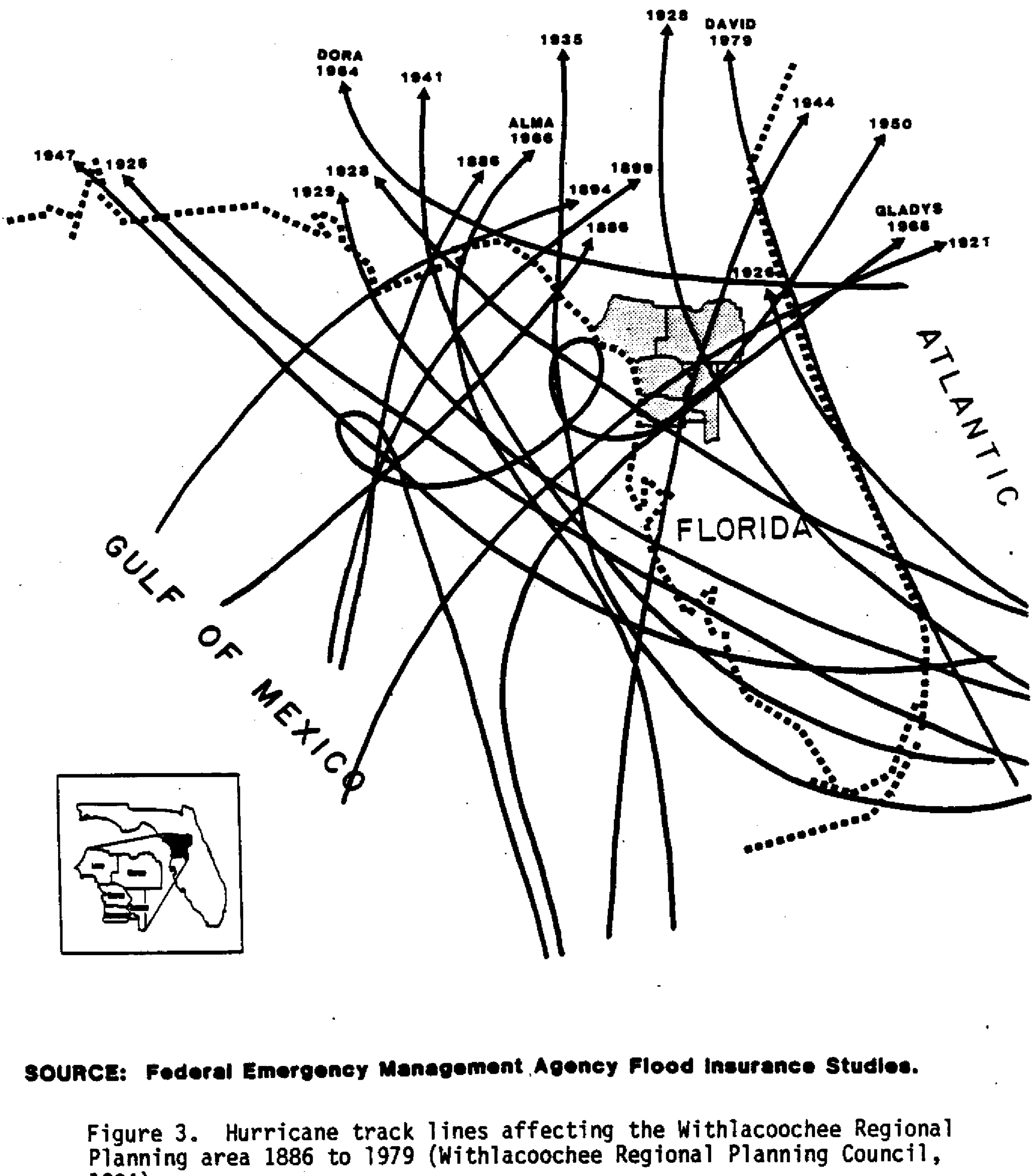
Date of Closest Point of Approach	Distance of Closest Point of Approach (nautical miles)	Wind[1] Speed (mph)	Storm[2] Intensity Category
1886-June 21	104	95	1
1886-July 1	48	97	2
1886-July 19	42	98	2
1888-Oct. 11	10	97	2
1893-June 16	39	86	1
1893-August 27	89	119	3
1894-Sept. 26	74	100	2
1894-Oct. 9	85	102	2
1896-Sept. 29	22	107	2
1898-Aug. 2	89	75	1
1898-Oct. 2	108	98	2
1899-Aug. 2	96	77	1
1921-Oct. 26	87	101	2
1925-Dec. 1	99	81	1
1926-July 28	19	81	1
1928-Sept. 17	32	118	3
1935-Sept. 4	43	95	1
1939-Aug. 12	77	79	1
1941-Oct. 7	112	87	1
1944-Oct. 19	45	75	1
1945-June 24	49	97	2
1945-Sept. 16	50	93	1
1947-Oct. 15	111	76	1
1949-Aug. 27	16	87	1
1950-Sept. 7 (Easy)	37	125	3
1950-Oct. 19 (King)	9	76	1
1960-Sept. 11 (Donna)	77	116	3
1964-Sept. 10 (Dora)	7	115	3
1966-June 10 (Alma)	67	98	2
1968-Oct. 19 (Gladys)	47	81	1
1979-Sept. 4 (David)	87	98	2

Notes: 1 - Maximum sustained wind speed near storm center while storm center is within 120 nautical miles of Crystal River. This is not necessarily the wind speed recorded at Crystal River.

2 - Highest storm intensity category achieved within 138 statute miles of Crystal River.

Source: National Hurricane Center, Miami.

HISTORY OF HURRICANE ACTIVITY IN THE WITHLACOOCHEE REGION



SOURCE: Federal Emergency Management Agency Flood Insurance Studies.

Figure 3. Hurricane track lines affecting the Withlacoochee Regional Planning area 1886 to 1979 (Withlacoochee Regional Planning Council, 1984).

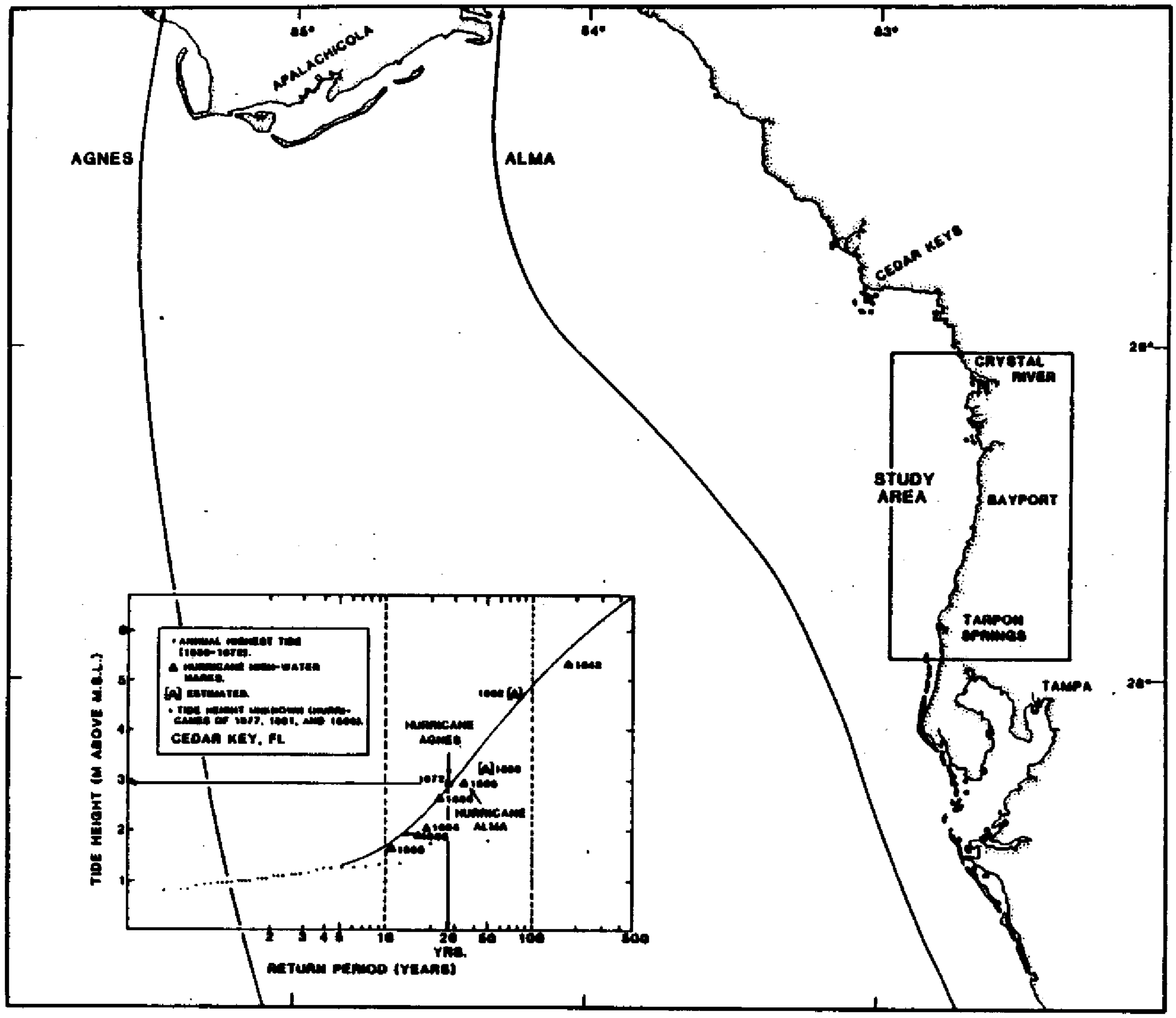


Figure 4. Map indicating tracks of Hurricanes Agnes and Alma-two storms whose surge or win tide have affected the study area in recent times. Insert shows high water marks of past hurricanes plotted on calculated curve for storms of different return periods (different size/strength hurricanes) for Cedar Key. (Data from Ho and Tracey, 1975). On the inset graph, a storm surge of 2m at Bayport yields a recurring frequency of about 10 years.

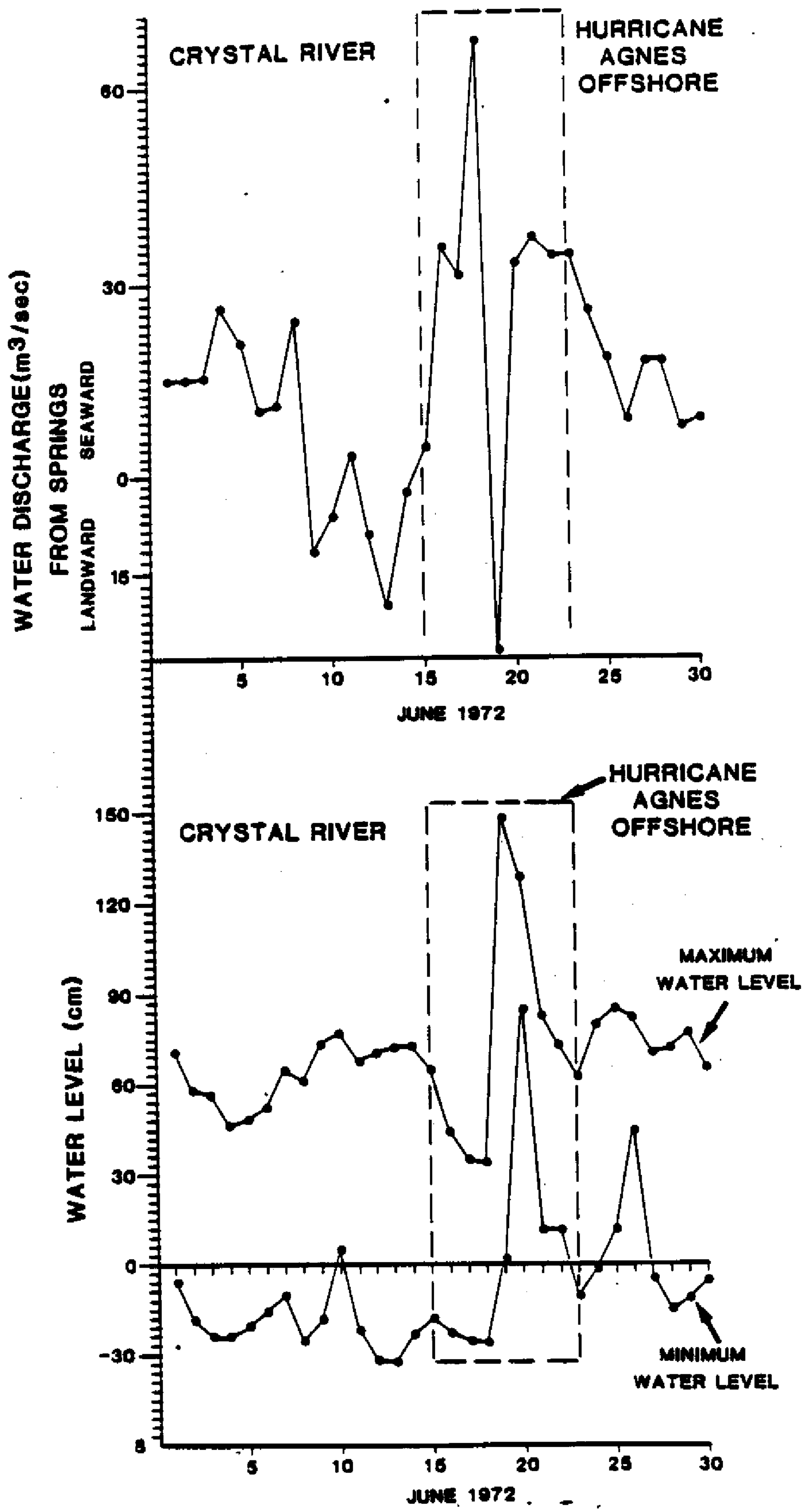


Figure 5. Fluctuations in water level (lower diagram) and water discharge from Crystal River (upper diagram) during passage offshore of Hurricane Agnes.

HISTORICAL SHORELINE CHANGES

Shoreline changes in the study area show wide variability, from unmeasureable stability over 37 years, (period over which aerial photographs were compared and measured) to more than 100 m (328 ft) of shoreline erosion. The agent which causes the greatest change is clearly human dredge and fill. Not all segments of the shoreline move simultaneously. Some remain stable for decades. This is probably indicative of the ability of marsh and oyster reef communities to keep up with rising sea level, unless devastated by a major storm. We would expect much greater evidence of erosion after a major hurricane. Of the natural shoreline segments that show erosion, there is a remarkable similarity in their rates of erosion, about one half meter (20 in) per year: 58 cm/yr (23 in/yr: Crystal Bay; 55 cm/yr (22 in/yr): Ozello; 42 cm/yr (16 in/yr): Bayport; and 44 cm/yr (17 in/yr): Bayonet Point. The oyster reefs in Crystal Bay also fit this scheme, showing 33 cm/yr (13 in/yr) change on the outer reefs and 53 cm/yr (21 in/yr) on the inner reefs, where changes occurred.

When compared to the potential rates of shoreline retreat estimated from sea-level rise, these rates seem somewhat small. The geologic rate of shoreline retreat should have averaged some 2.7 m/yr (8.9 ft/yr) over the past 3000 years, and based on the tide gauge data for the past 60 years, shoreline retreat should have been four times faster than that. This last point suggests that widespread shoreline changes may occur during the direct passage of a major hurricane.

PHYSICAL CHARACTERISTICS OF HURRICANE ELENA

Storm Formation and Storm Track

The formation of the weather system that led to the development of Hurricane Elena occurred as an organized cloud pattern passing out of the Sahara Desert on August 23,1985. This system rapidly tracked across the Atlantic Ocean, but did not become a tropical storm until August 27 as it was approaching Cuba (Fig. 6). With the discovery of 50 knot winds on August 28 by a reconnaissance aircraft, the low pressure system was named Tropical Storm Elena. Tropical Storm Elena rapidly became Hurricane Elena on August 29 as it entered the Gulf of Mexico. The Hurricane continued to track in a northwesterly direction until an extratropical frontal trough moving across the continental U. S. caused Elena to stop and drift slowly toward the east for a 36 hour period spanning August 31 to September 1 (Fig. 7). As atmospheric pressure began to increase over the eastern United States, Hurricane Elena resumed its track toward the northwest and began to strengthen as well. By late afternoon on September 1 (see Table 2), the atmospheric pressure at the center of the Hurricane was at its lowest (951 mb-measured) and maximum winds were calculated to be 110 knots (Class 3 on Saffir/Simpson scale). Hurricane Elena passed over the Mississippi coast near Biloxi on September 2 and was downgraded to tropical storm status late that afternoon (Information gathered from a preliminary report generated by the National Hurricane Center).

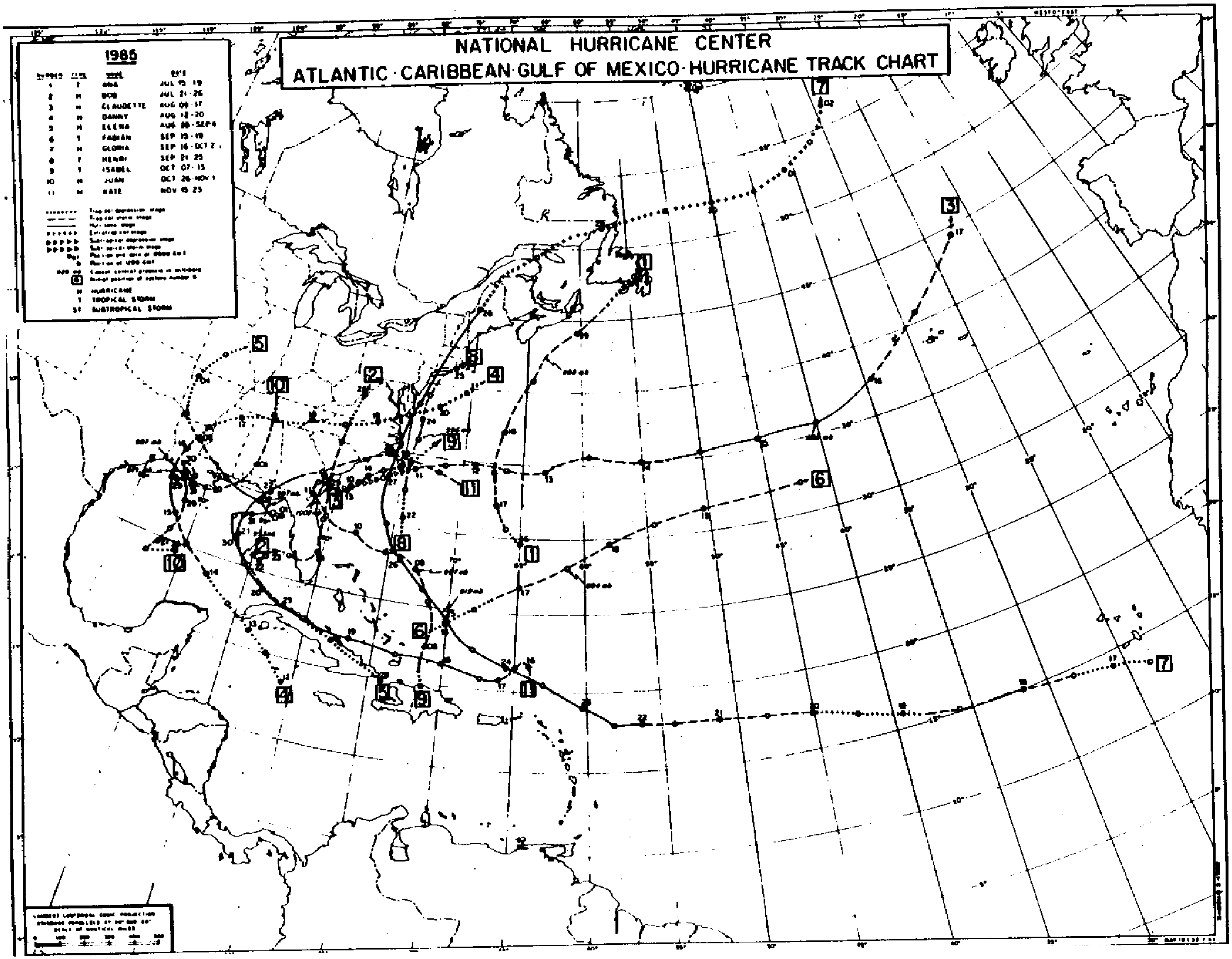


Figure 6. Tracks of the 1985 hurricanes. Hurricane Elena is track #5 (National Climatic Data Center, 1985).

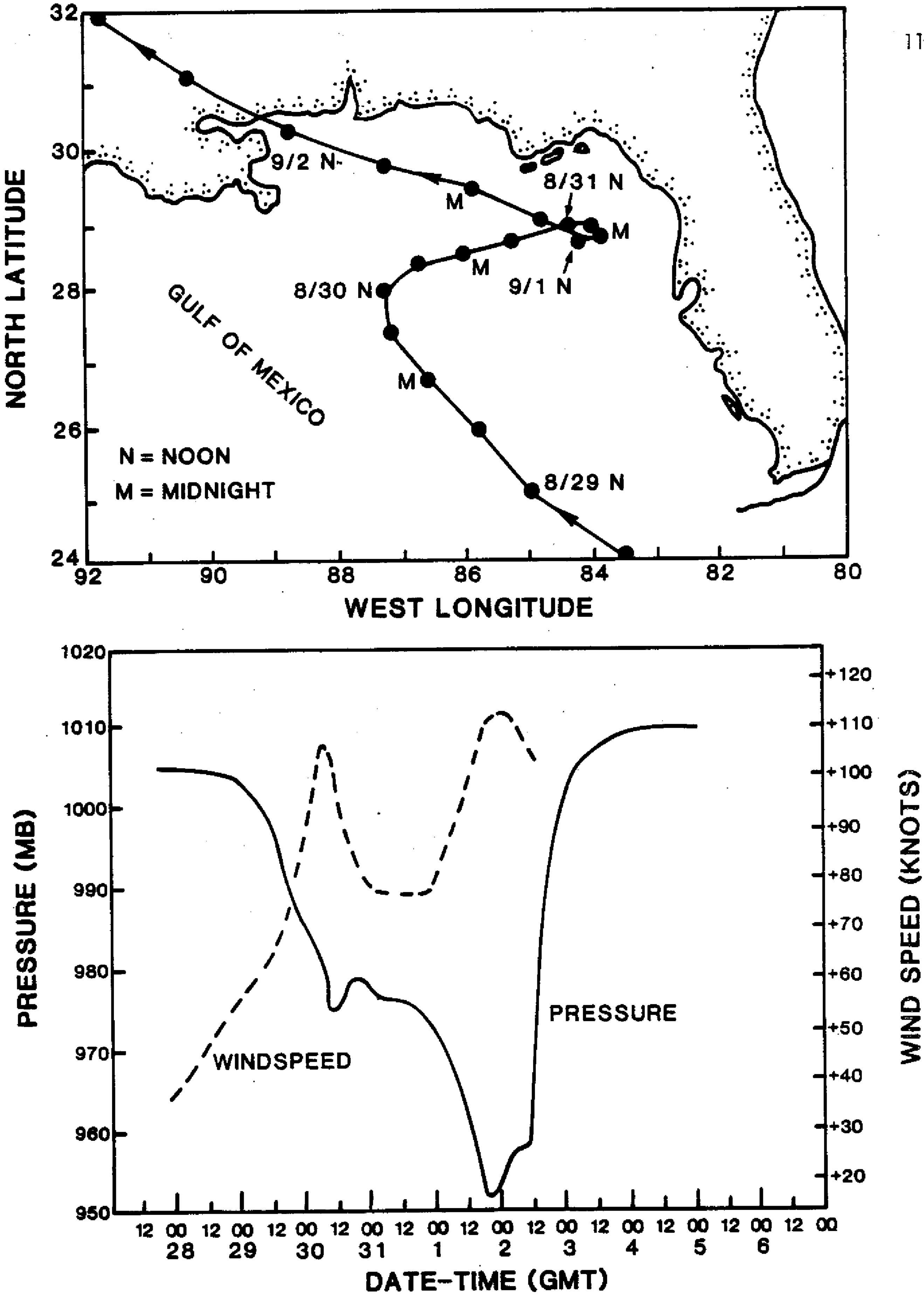


Figure 7. Detailed track line of Hurricane Elena and atmospheric pressure/wind speed through time.

TABLE 2

PRELIMINARY BEST TRACK - HURRICANE ELENA

28 AUGUST - 4 September 1985

DATE	TIME (GMT)	POSITION LAT.	LONG.	PRESSURE (MB)	WIND (KT)	STAGE
8/28	0000	19.8	74.0	1012	30	Tropical Depression
	0600	20.8	76.0	1010	30	" "
	1200	21.8	78.0	1008	30	" "
	1800	22.6	80.0	1006	45	Tropical Storm
8/29	0000	23.2	81.8	1004	50	" "
	0600	24.0	83.5	1000	55	" "
	1200	25.0	85.0	994	65	Hurricane
	1800	25.9	85.8	990	70	"
8/30	0000	26.6	86.6	986	75	"
	0600	27.3	87.2	980	80	"
	1200	27.9	87.3	974	90	"
	1800	28.3	86.8	978	90	"
8/31	0000	28.4	86.0	977	90	"
	0600	28.6	85.3	976	90	"
	1200	28.8	84.4	975	90	"
	1800	28.8	84.0	974	90	"
9/01	0000	28.8	83.8	971	95	"
	0600	28.6	83.9	965	100	"
	1200	28.6	84.2	961	105	"
	1800	28.9	84.8	954	110	"
9/02	0000	29.4	85.9	953	110	"
	0600	29.7	87.3	957	105	"
	1200	30.2	88.8	959	100	"
	1800	31.0	90.4	990	60	Tropical Storm
9/03	0000	31.9	91.8	1000	45	" "
	0600	32.4	92.8	1004	30	Tropical Depression
	1200	33.2	93.7	1006	25	" "
	1800	34.5	94.0	1008	25	" "
9/04	0000	35.9	93.9	1010	20	" "
	0600	37.0	93.2	1010	20	" "
	1200	38.0	92.5	1010	20	" "
	1800	38.8	91.4	1010	20	" "

Landfall at:

9/02	1300	30.4	89.2	959		Hurricane

It is important to note that Hurricane Elena's closest location to the west-central Florida coast was 81 km (45 nm) from Cedar Key at midnight between August 31 and September (Figs. 7, 8). Maximum wind velocity associated with the storm at that time was 95 knots. By the time Elena reached its peak wind velocity of 110 knots, the Hurricane was 165 km (91 nm) away and heading off to the west-northwest.

Of the 700 tropical storms and hurricanes that passed over or near Florida since the late 1800's, no more than two dozen have had tracks as erratic as Hurricane Elena. This slow and erratic movement by this hurricane feigning landfall caused unusual problems for disaster preparedness and emergency personnel (Bodge and Kriebel, 1985).

Wind Circulation, Water Levels, Waves

While Hurricane Elena was drifting offshore, the location and size of the storm determined wind direction patterns along the coast (Fig. 9). Since hurricanes have counterclockwise circulation in the northern hemisphere and this particular hurricane was located roughly due west of the study area, the dominant winds blew alongshore or even slightly offshore. Further to the south, in Pinellas County, dominant winds were onshore, blowing from the southwest. No doubt that this was a contributing factor to the relatively large amount of damage done to the sandy beaches, seawalls, and buildings located along that county's shore (7.8 miles of destroyed or heavily damaged open-ocean seawalls). Even though the Pasco, Hernando, and Citrus County coastline was located closer to the storm than Pinellas County, the alongshore direction of the winds prevented a higher storm surge from developing.

Maximum winds at Cedar Key were 87 knots during August 31. Peak gusts at Clearwater and Tampa International Airport were 60 and 39 knots, respectively (Bodge and Kriebel, 1985). Further inland, wind velocities were reduced as shown by wind data from Brooksville, FL where maximum sustained winds were only 20 knots with gusts up to 35 knots (Table 3).

Storm-tide driven water levels for the study area are shown in Figure 10. Note that the highest water level was recorded at the Bayport tide gauge (2m above mean sea level). Note that water levels remained elevated for about a 32 hour period from 0000 hours August 31 to 0800 hours September 1. Finally, a pre-storm water elevation (storm set-up) can be seen during August 29 and 30 as Elena was approaching from the west.

Along the entire Florida coast affected by Elena, peak storm tide elevations are shown in Figure 11. Note the absence of data along the marsh-dominated coast (Wakulla through Pasco County). The lone data point is from Cedar Key in Levy County measured by an NOS (National Ocean Survey) tide gauge. Peak water levels actually measured inside rooms in a building fronting the open Gulf on Cedar Key indicated that the storm surge reached 2.78 m (9.2 ft) above mean sea level (Bodge and Kriebel, 1985). The storm surge north of Cedar Keys was estimated to be only about 30-60 cm (1-2 ft), probably due to the dominance of the offshore blowing winds.

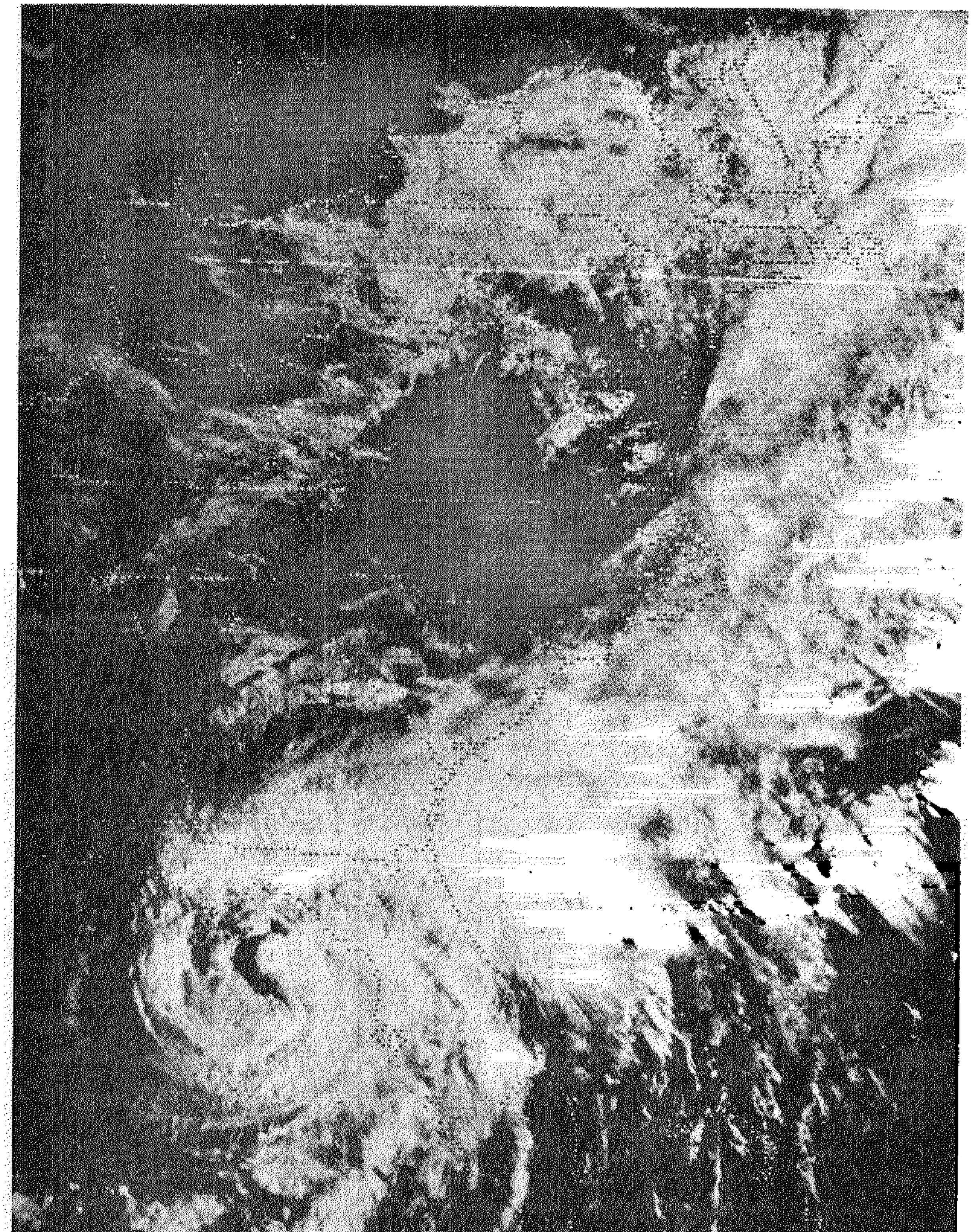


Figure 8. Space image (GOES 6 satellite) of Hurricane Elena early morning August 31, 1985. This location is about as close that the storm came to the west-central Florida coast. The storm started to move to the west as a result of the cold front moving off the Atlantic coast (National Climatic Data Center, 1985).

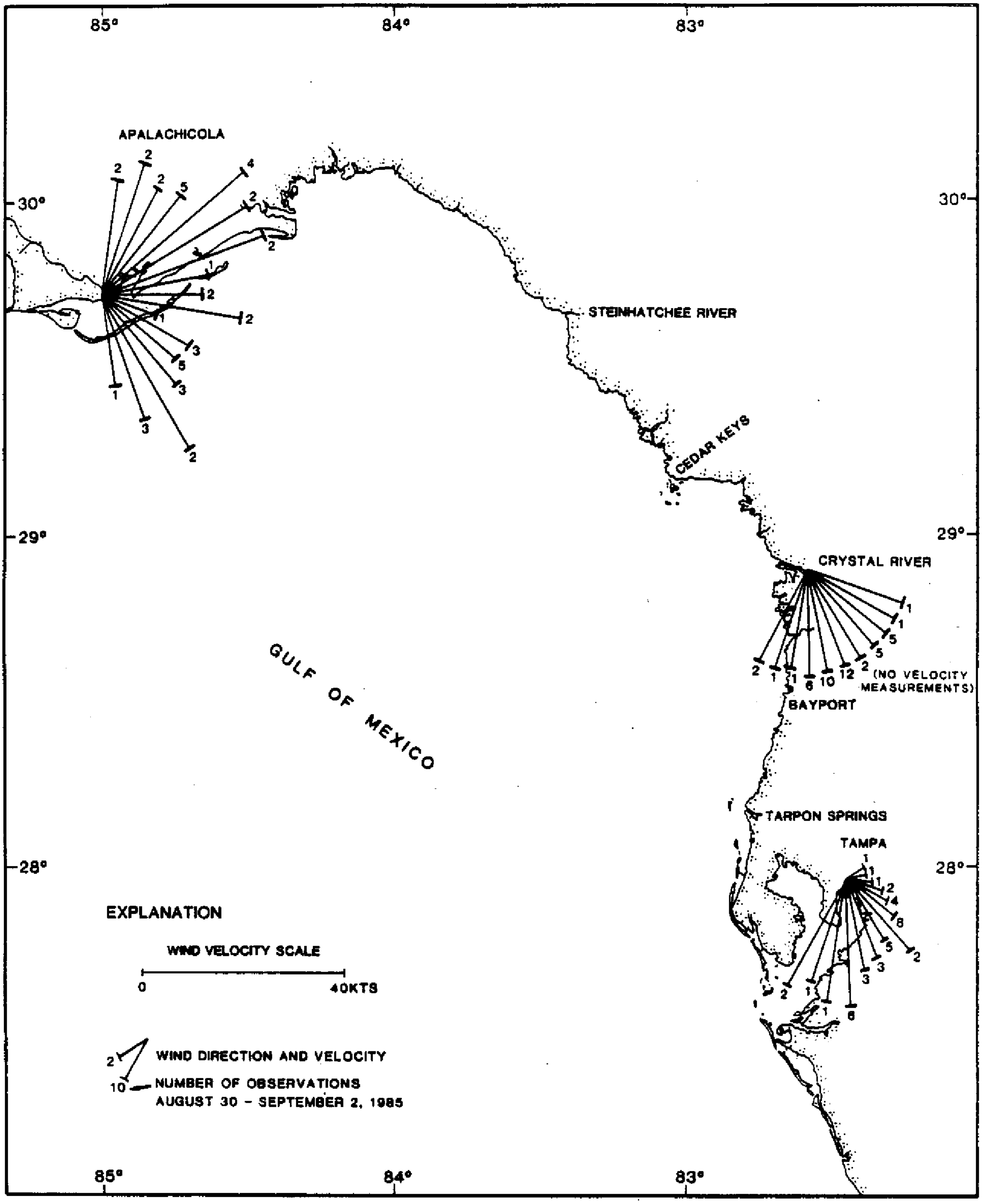


Figure 9. Distribution of winds during August 30-September 2, 1985 at three locations around the west Florida coast. Orientation of wind direction illustrates general counter-clockwise circulation of Elena. Unfortunately, no wind velocity measurements were available from the Crystal River station. Note that in the Crystal River area, most of the wind direction readings indicate an alongshore or slightly offshore orientation. The strongest winds in the Tampa area were onshore.

TABLE 3

WIND DATA FROM WITHLACOOCHEE FOREST CENTER, BROOKSVILLE, FL

DATE	WIND DIRECTION	SPEED
8-28-85	South East	12
8-29-85	East	10
8-30-85	East	8
8-31-85	East	20, G-35
9-1-85	South East	20
9-2-85	South East	12
9-3-85	South East	6
11-20-85	North East	10
11-21-85	South East	18
11-22-85	South West	12
11-23-85	North	1

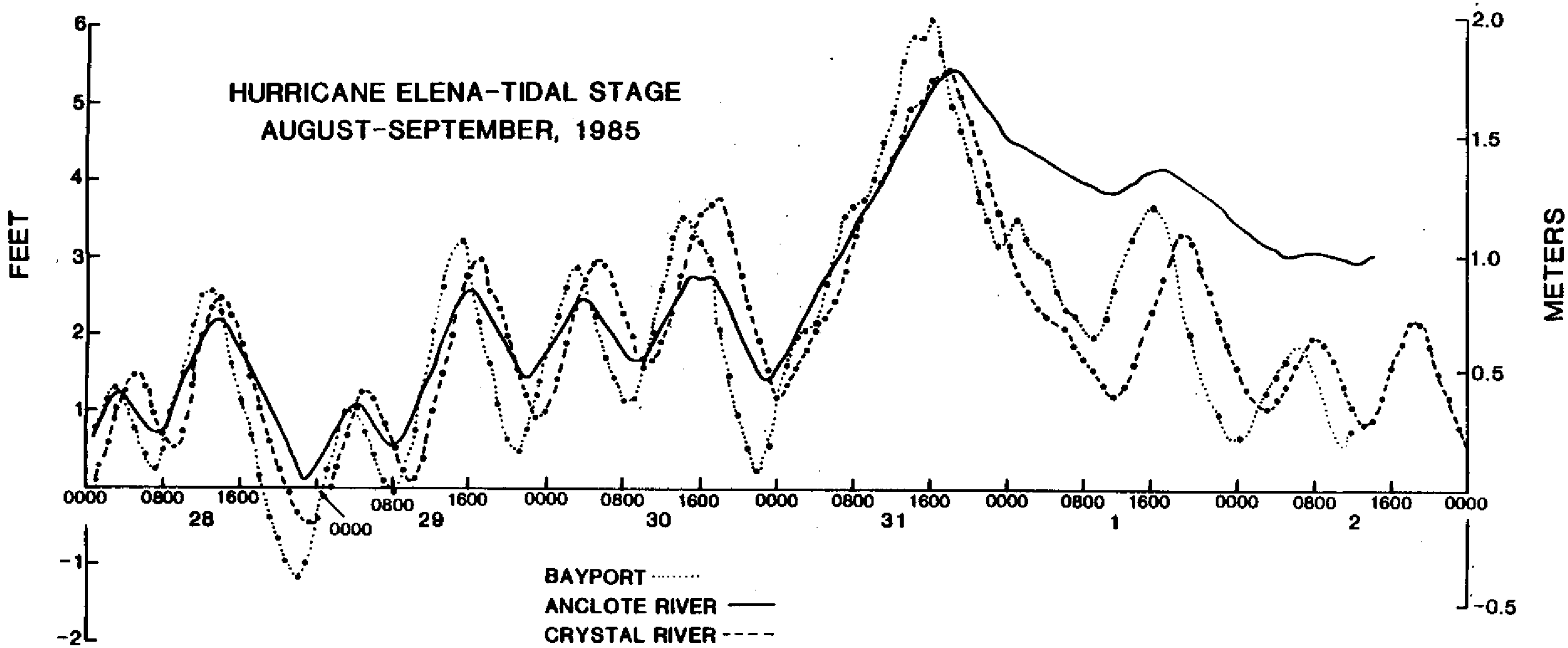


Figure 10. Water level measurements from Bayport, Anclote River, and Crystal River during Hurricane Elena. The highest level recorded was from the Bayport tide gauge which provided a 2m reading at 1600 hours on August 31, 1985.

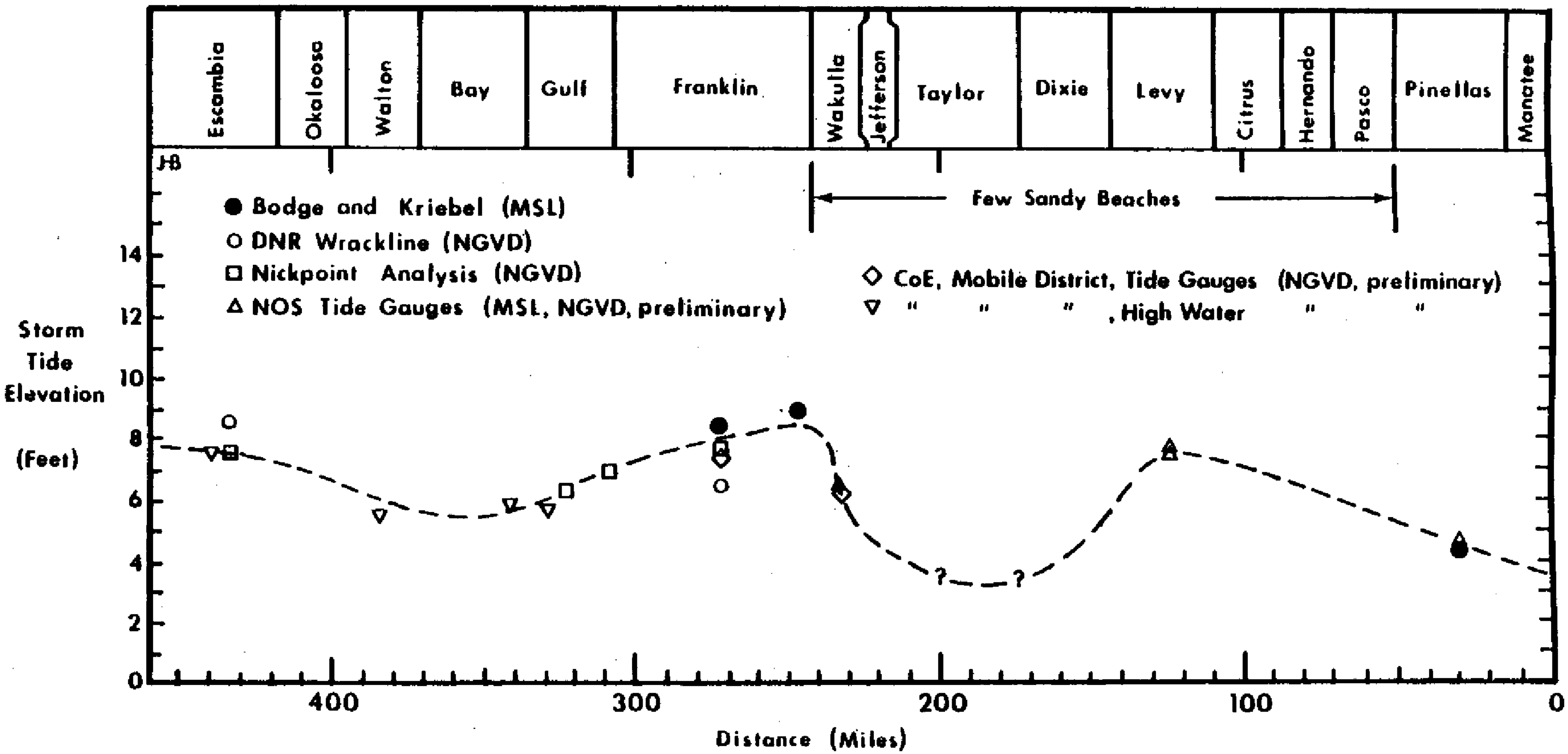


Figure 11. Peak storm-[illegible] feet) from Hurricane Elena along the Gulf coast of Florida (Figure 9 of Balsillie, 1985).

To the south of the study area, maximum storm surge (1100 hrs, August 31) at Clearwater was estimated to be 1.39 m (4.6 ft) above mean sea level (Bodge and Kriebel, 1985).

Wave parameters (height and period) were recorded by the University of Florida's Coastal Data Network station at Clearwater. Here, a peak significant wave height of 2.48 m (8.2 ft) was measured at 1400 hours on August 31 (Fig. 12). Corresponding wave period was 13 sec. Unfortunately, the wave gauge at the Steinhatchee CDN station was not operating. Since the regional gradient of the inner continental shelf is flatter in the Pasco, Hernando, and Citrus County coastal area and the seafloor located at a higher (shallower) elevation than those conditions off Clearwater, one can only assume that wave heights were not as large along the northern Suncoast.

COMPARISON OF HURRICANE ELENA TO HURRICANE KATE

Hurricane Kate passed over the central portion of the Gulf of Mexico from November 20-22, 1986. Although this storm had similar dimensions as Hurricane Elena (Fig. 13A) it passed by the Pasco, Hernando, and Citrus County coastline further offshore (nearly 300 km seaward) and moved along much more rapidly than Elena. The effects on the Pasco, Hernando, and Citrus County coast were minimal. The storm surge associated with Kate was only 60 cm (2 ft) higher than a normal spring high tide (Fig. 13B). Wave data for Hurricane Kate from both the Clearwater and Steinhatchee gauge are shown (Fig. 14A,B).

EFFECTS OF HURRICANE ELENA

Overall, around the Gulf of Mexico basin, the effect of Hurricane Elena on human activity and property was dramatic. Approximately 537,000 people were evacuated from low-lying areas and housed in shelters. This was the largest number ever recorded. Only four deaths were reported-perhaps as a result of this large evacuation effort.

According to a preliminary, unpublished report from the National Hurricane Center, insured losses from Hurricane Elena were the fourth largest on record ($534,000,000 reported to the American Insurance Services Group). This report was written before Hurricane Juan which apparently caused more property damage than Elena (Table 4).

Within the Pasco, Hernando, and Citrus County coast, very little damage was done to property. In addition, very little change occurred along the natural coastline. There are a number of reasons for this: (1) Elena never actually came ashore-the eye came within 81 km of Cedar Key, (2) winds were generally from the south or alongshore, (3) the coast was not subjected to hurricane force winds, (4) the resulting storm surge was only 2 m above mean sea level, (5) the low shelf gradient prevented generation/propagation of large storm waves, (6) the baffling effect by marsh grasses, and (7) the relative low density of human habitation within this broad, coastal marsh system.

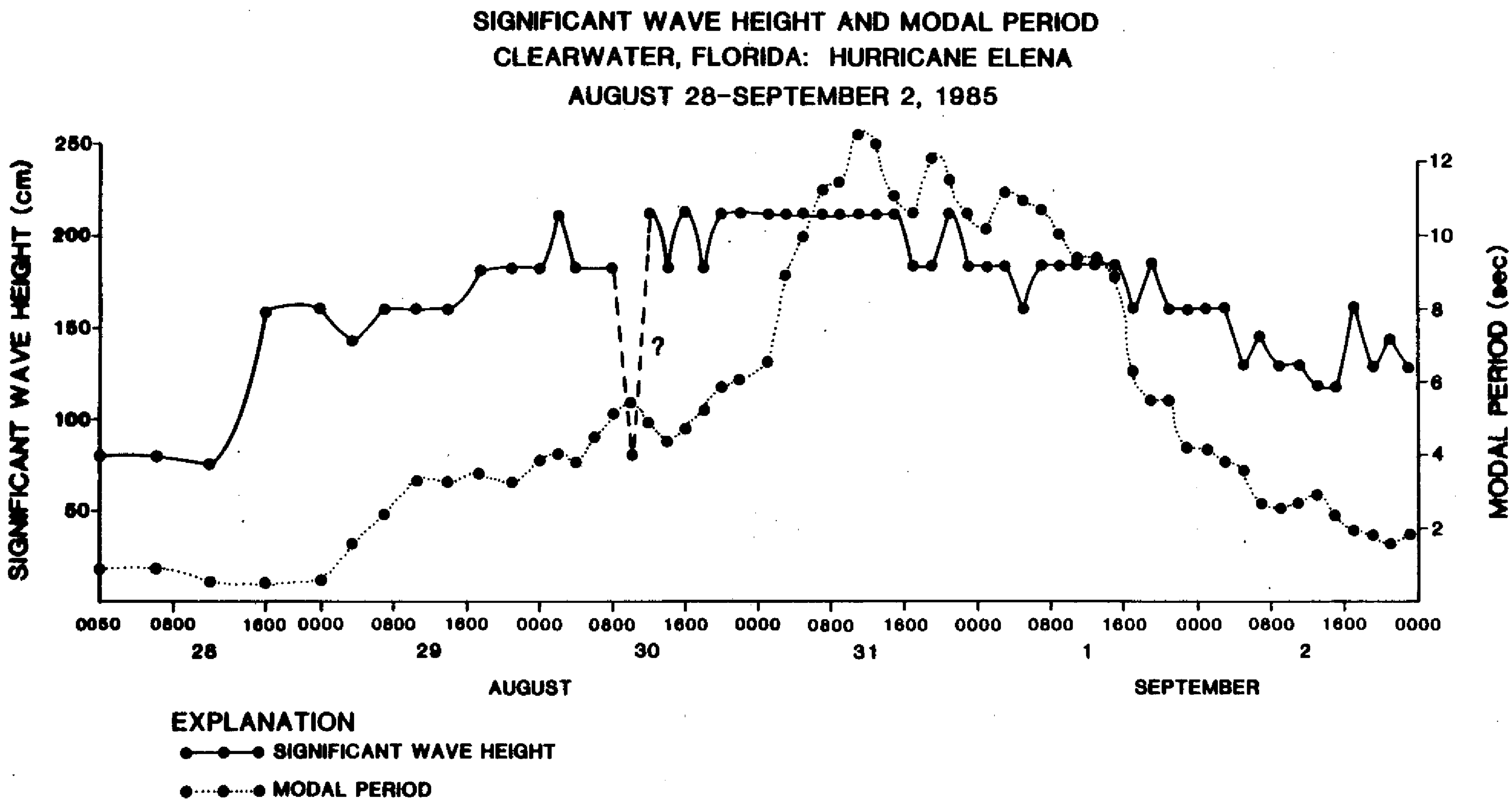
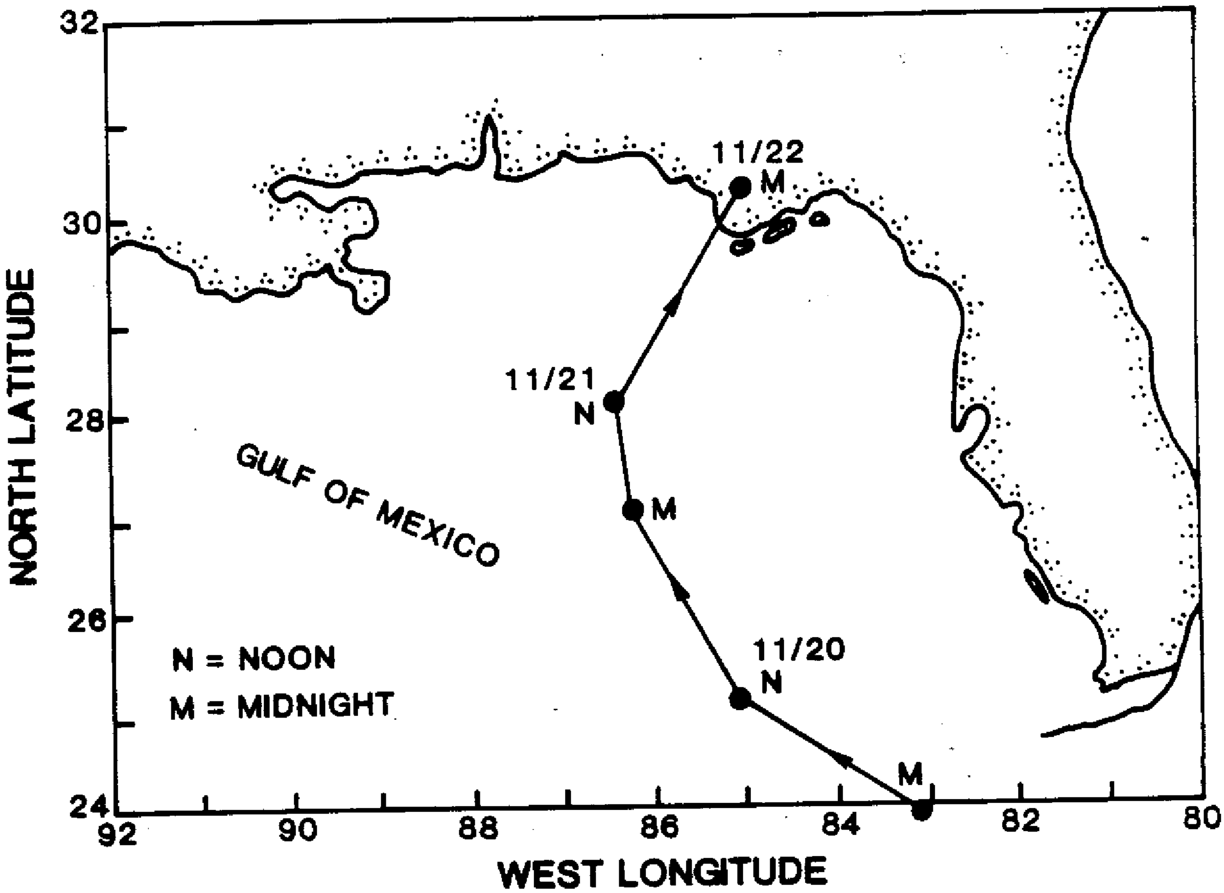


Figure 12. Graph showing significant wave height and modal wave period from the Clearwater wave gauge during Hurricane Elena. Note the long duration (nearly 48 hours) of the highest waves. This was probably one of the contributing reasons why there was so much damage done to the sandy shoreline of Pinellas County. This wave gauge is located out in approximately 13 m of water.



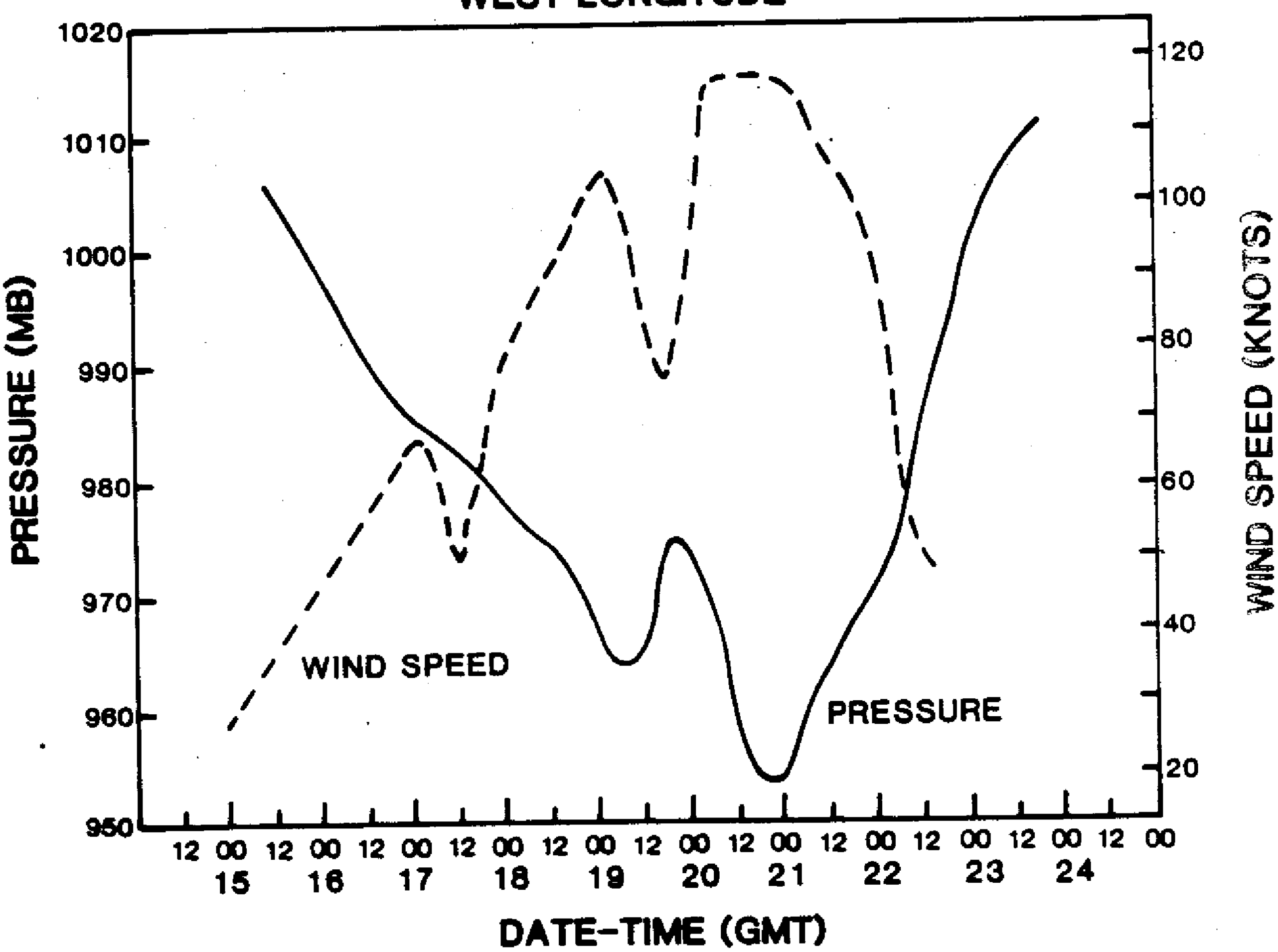


Figure 13A. Track of Hurricane Kate and associated atmospheric pressure and wind speed associated with that storm. This hurricane had a relatively small impact on the marsh-dominated coastline.

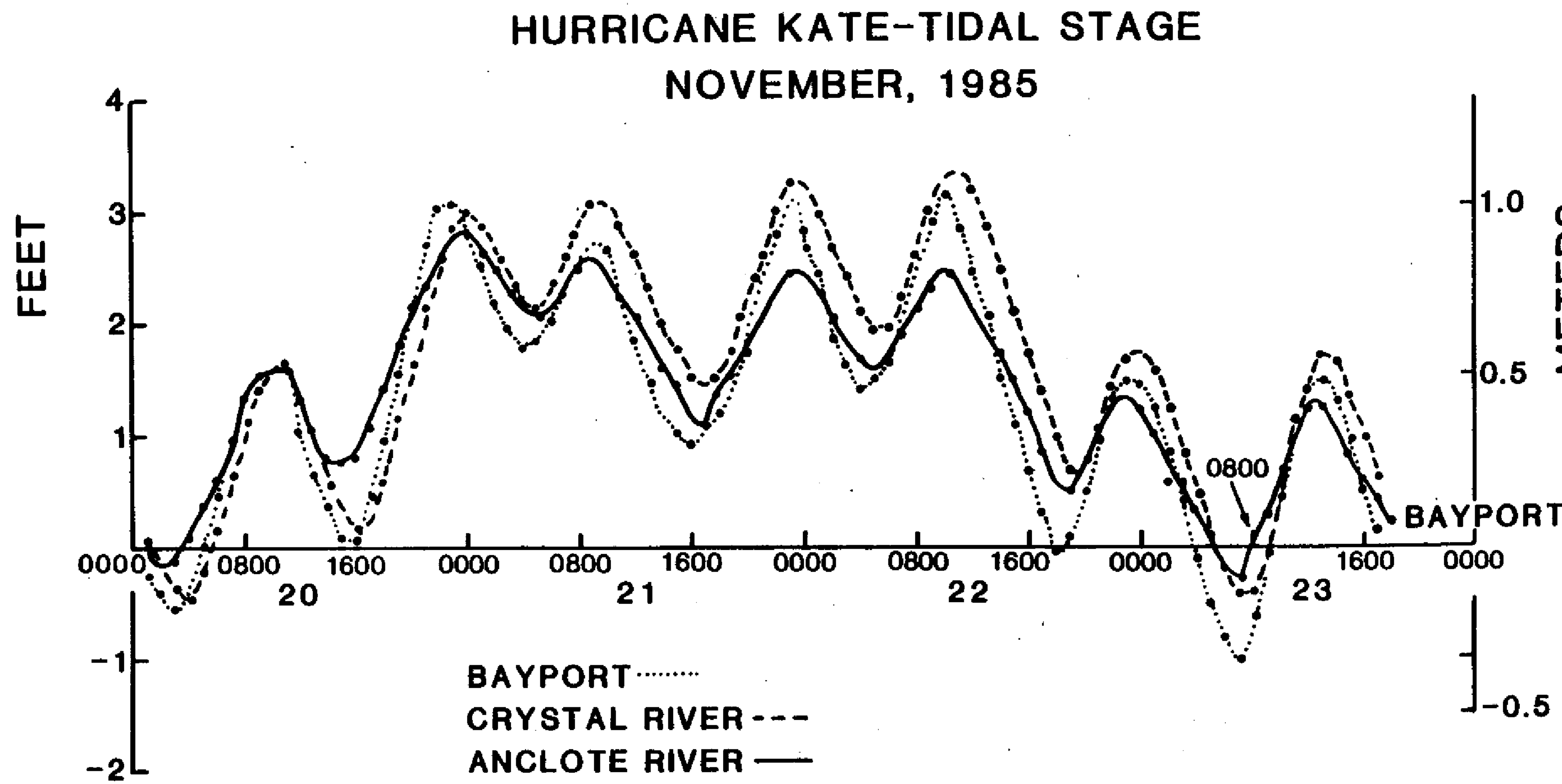


Figure 13B. Water level measurements from Bayport, Anclote River, and Crystal River during Hurricane Kate. The highest level recorded was slightly over 1m at Crystal River. This storm tide was about 50% of Hurricane Elena's storm tide.

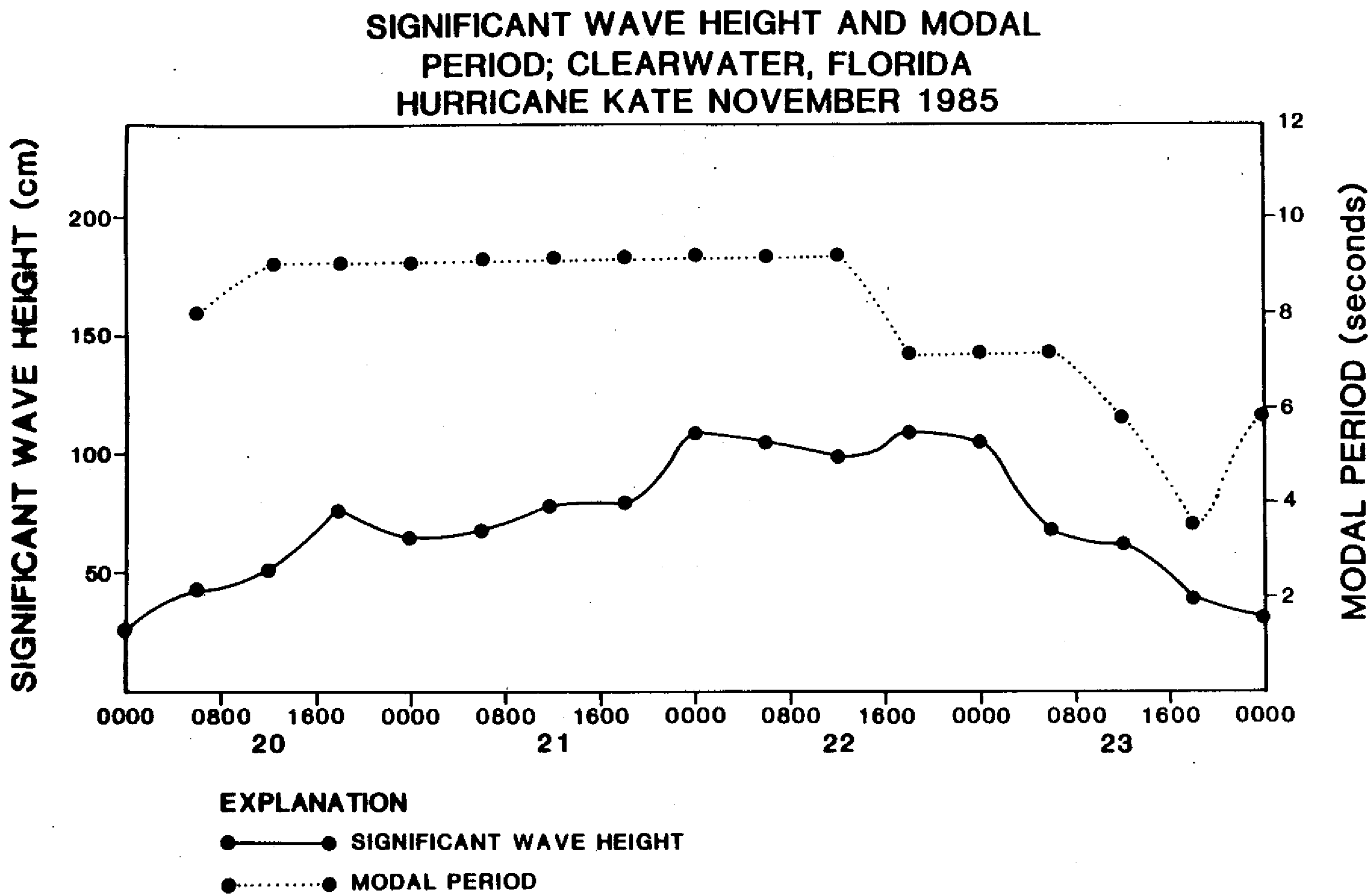


Figure 14A. Graph showing significant wave height and modal wave period from the Clearwater wave gauge for Hurricane Kate. Wave height at this location from this hurricane was much lower than Hurricane Elena.

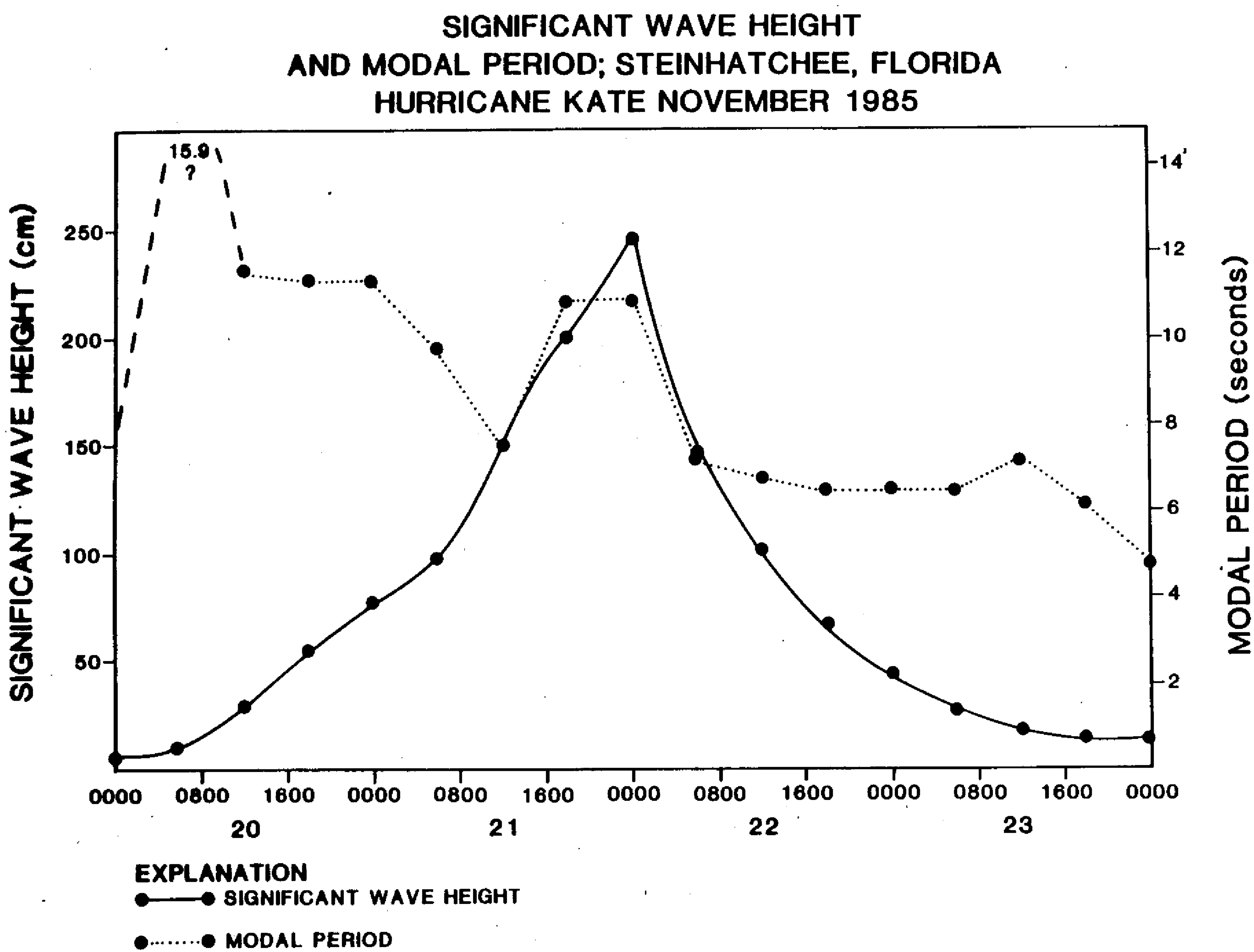


Figure 14B. Graph showing significant wave height and modal wave period from the Steinhatchee wave gauge for Hurricane Kate. This hurricane made landfall over the Apalachicola River delta just off to the west. The close proximity of this wave gauge station the Hurricane Kate accounts for the relatively large waves measured here (250 cm/8.25 ft).

TABLE 4

SUMMARY OF NORTH ATLANTIC TROPICAL CYCLONE STATISTICS, 1985
(CLARK AND CASE, 1986)

Cyclone Number	Name	Class[1]	Dates[2]	Maximum Sustained Winds (kn)	Lowest Pressure (mb)	U.S. ($ Damage) (millions)	Deaths
1	ANA	T	7/15-7/19	60	996		
2	BOB	H	7/21-7/26	65	1002		
3	CLAUDETTE	H	8/09-8/17	75	980		
4	DANNY	H	8/12-8/20	80	987	50	1
5	ELENA	H	8/28-9/04	110	951	1250	4
6	FABIAN	T	9/15-9/19	55	992		
7	GLORIA	H	9/16-10/02	125	919	900	8
8	HENRI	T	9/21-9/25	50	996		
9	ISABEL	T	10/07-10/15	60	997		
10	JUAN	H	10/26-11/01	75	971	1500	12
11	KATE	H	11/15-11/23	105	953	300	5

1 T: Tropical storm, wind speed 34-63 kn.
H: Hurricane, wind speed 64 kn or higher.

2 The day begins at 0000 GMT.

In the Crystal River area, a local scientist living near the marsh system west of the Salt River on Route C-44 claimed that his own house, which is 1.5 m (5 ft) above sea level, was not flooded. In addition, there was very little erosion of the marsh islands and oyster bars. It was observed, however, that the spoil banks associated with the Crystal River nuclear power plant were noticeably eroded. Other observers noted some wind damage (trees blown down), but concluded that coastal flooding was little more than a normal spring tide. Flooding problems were more the result of rainfall.

Our own observations from the ground and several overflights generally coincided with the general conclusion that Hurricane Elena did not make a significant impact upon the open-marine coastline. Unfortunately, no vertical aerial photography was commissioned by State agencies such as DOT or DNR right after the storm to assess storm impact. We conducted two overflights from light aircraft. The basic observations from these overflights are illustrated in Figures 15-21.

From south to north, we made the following observations from a low altitude overflight made in September, 1985. Figure 15 illustrates two new breaks or cuts made into the marsh forming small, sand-starved washover fans (Pasco County). Figure 16 shows a submerged sand spit that has enlarged as a result of waves breaking during the storm thus transporting sands in an alongshore direction (Pasco County). Figures 17 and 18 show a prominent, new Juncus wrack in the higher marsh areas (Hernando County). Figures 19 and 20 show dead mangrove plants (killed by earlier freezes) and trees blown down by Elena's winds (Citrus County). Figure 21 illustrates the top of an oyster bioherm in Crystal Bay, seaward of the Crystal River. Very little change was seen on these features except for the crest which had been modified by waves and currents. The lightest portion of the crest represents new oyster shell transport resulting from the storm.

We reoccupied two beach profile stations after the storm. The northern station on Shell Island at the entrance to Crystal River showed no change. The other profile (PC-2) located on Bayonet Point in Pasco County did show measureable change (Figure 22). This station is along the berm-ridge coastal sector. One can see that the berm-ridge has migrated several meters onto the marsh surface. The most important change is along the beachface and lower intertidal, shallow subtidal zone where the profile has been lowered about 30 cm (1 ft). This represents a lateral translation of the ravinement surface and a shoreline erosion of about 7 m. Further seaward there is no change.

Along the berm-ridge coast, roots of dead mangroves (from earlier freezes) were nearly exposed indicating that this coastal sector did undergo some shoreline retreat. This contrasts with the marsh archipelago and shelf embayment coasts to the north which had little change. One would expect this trend since the winds were more onshore further to the south and also, the berm-ridge coast is less stabilized by marsh plants/mangroves. The berm-ridge coast also has more sand which is noncohesive and therefore more easily transportable than marsh sediments which front the open Gulf further to the north.

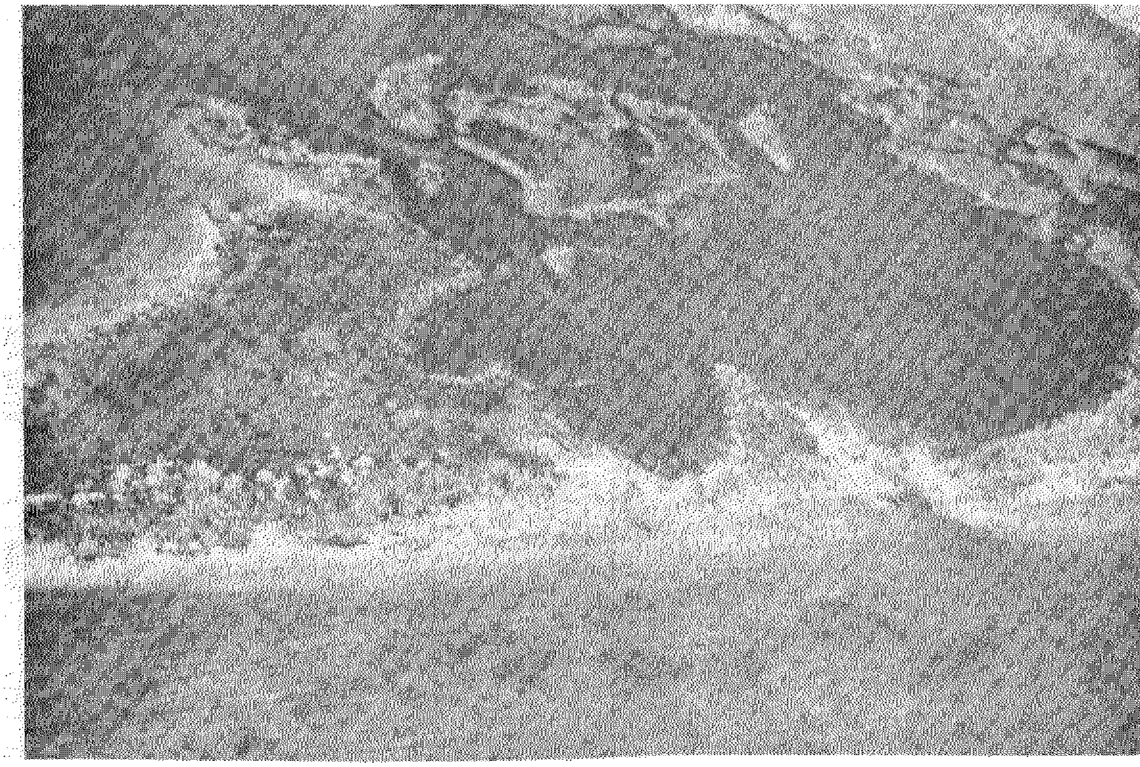


Figure 15. Low altitude, oblique aerial photo of marsh coast in Pasco County illustrating two small cuts in seaward marsh and small, sand-starved washover fans associated with them.

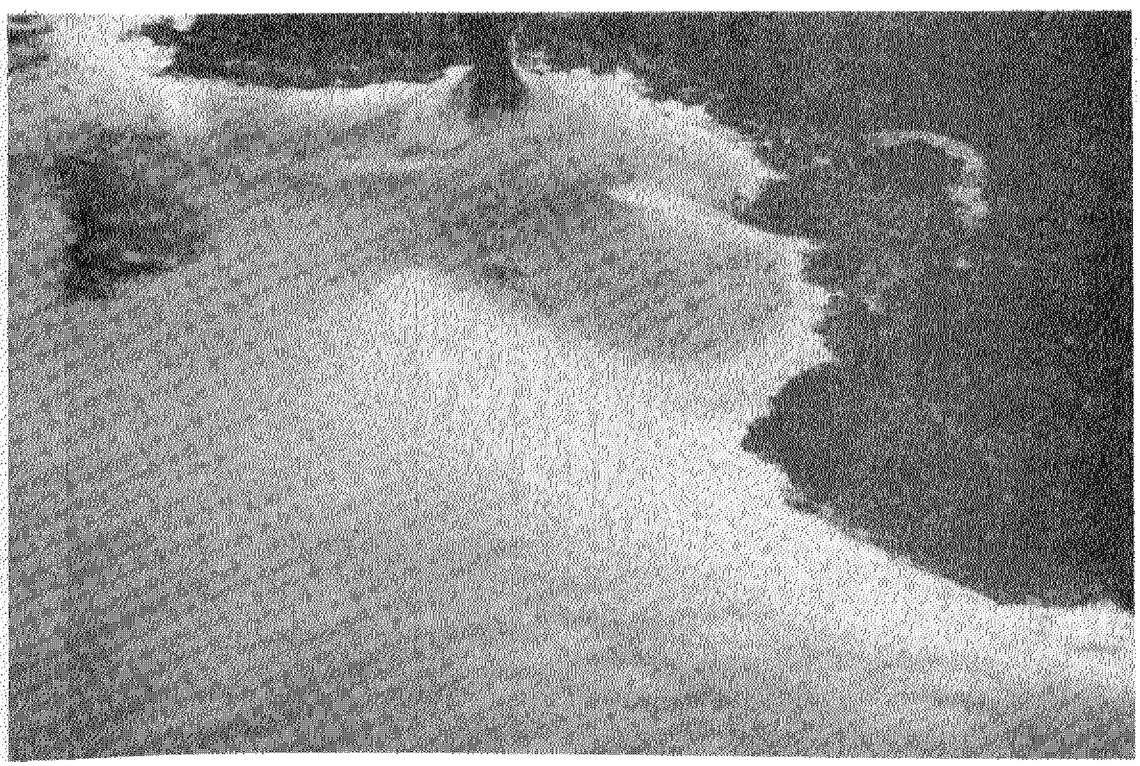


Figure 16. Low altitude, oblique aerial photo of a small, submerged recurved spit that has been enlarged/lengthened by wave activity associated with Hurricane Elena. Photo from northern Pasco County.

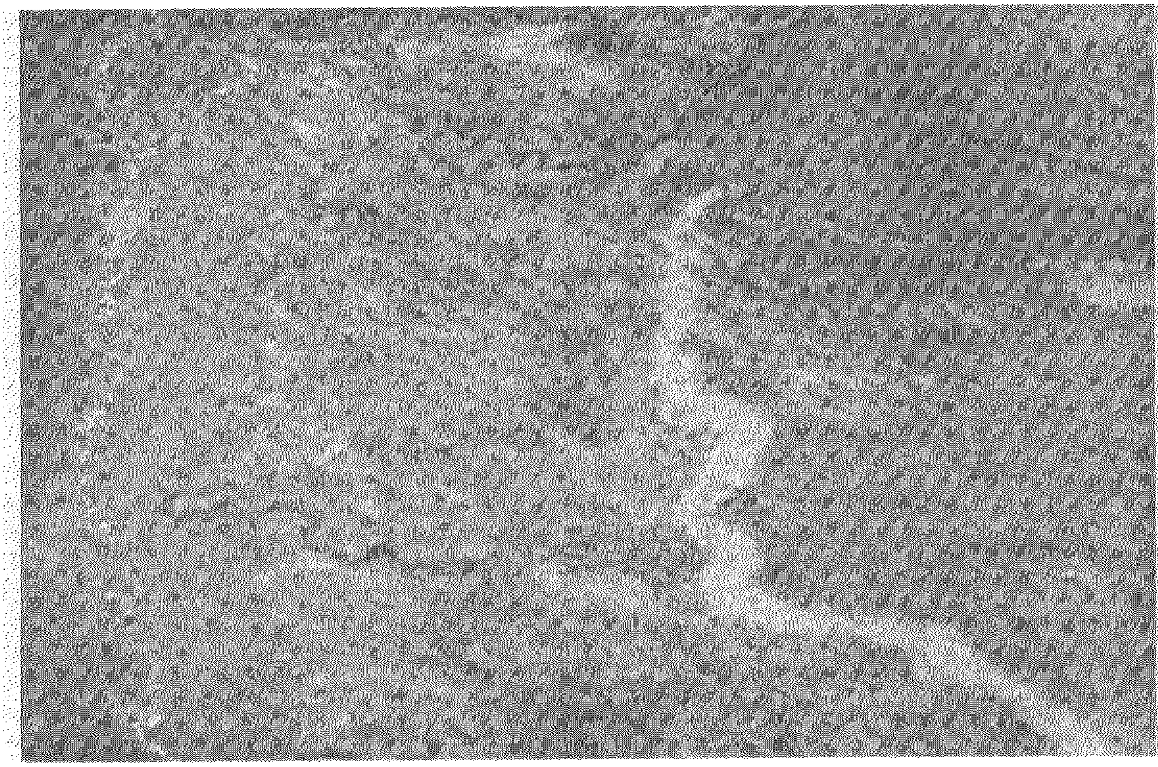


Figure 17. Low altitude, oblique aerial photo of new, extensive Juncus wrack in high marsh along Hernando County coast.

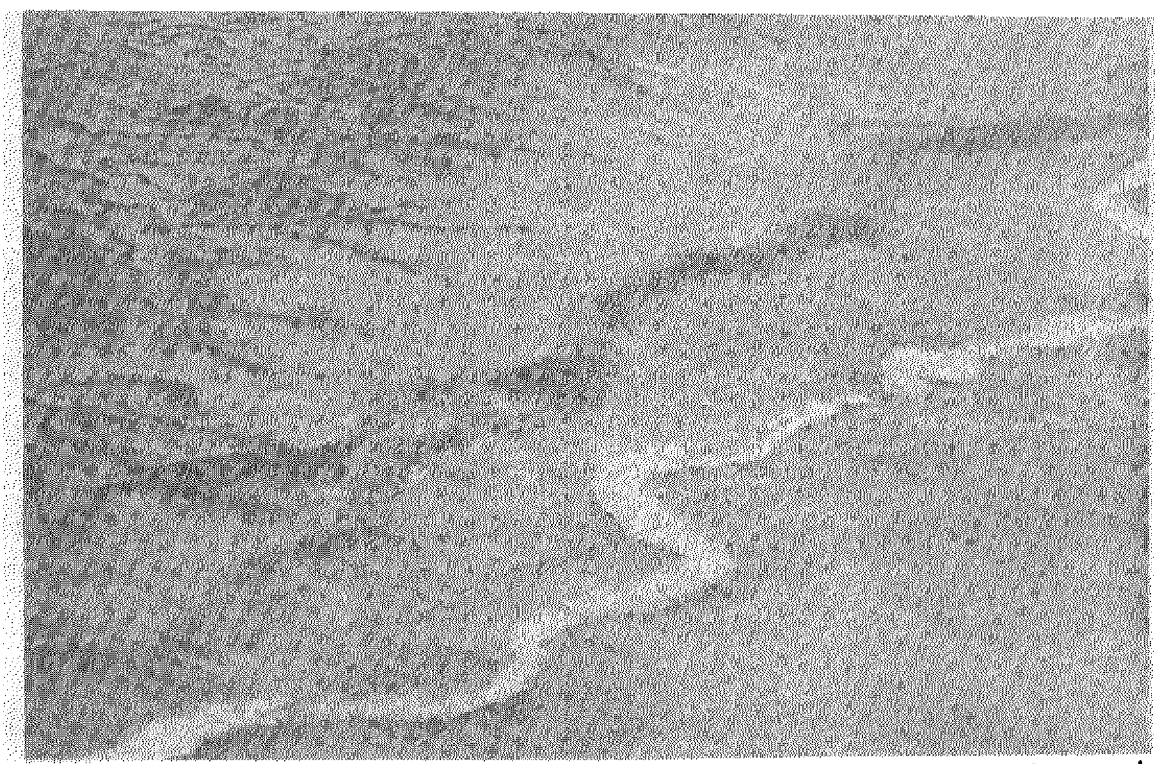


Figure 18. Low altitude, oblique aerial photo of Juncus wrack in marsh along Hernando County coast. This new, prominent windrow of marsh grass was a ubiquitous feature seen from the air.

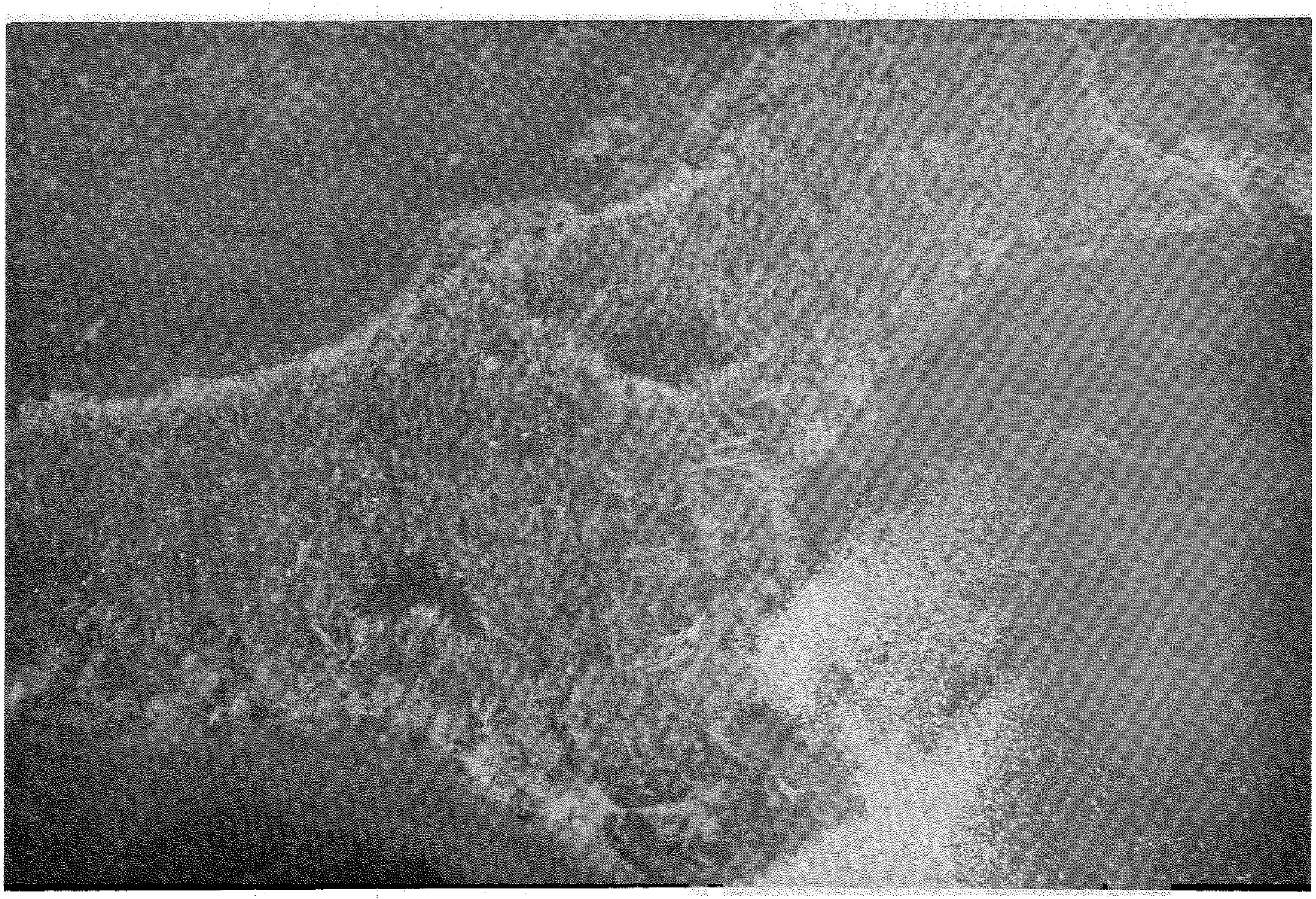


Figure 19. Low altitude, oblique aerial photo of a marsh/dead mangrove island in the marsh archipelago section of the Citrus County coast. Note the new erosion along the edge of the island in the lower center of the photo. Also, note the broken limbs and trunks of the dead mangrove plants which has been killed by earlier freezes.

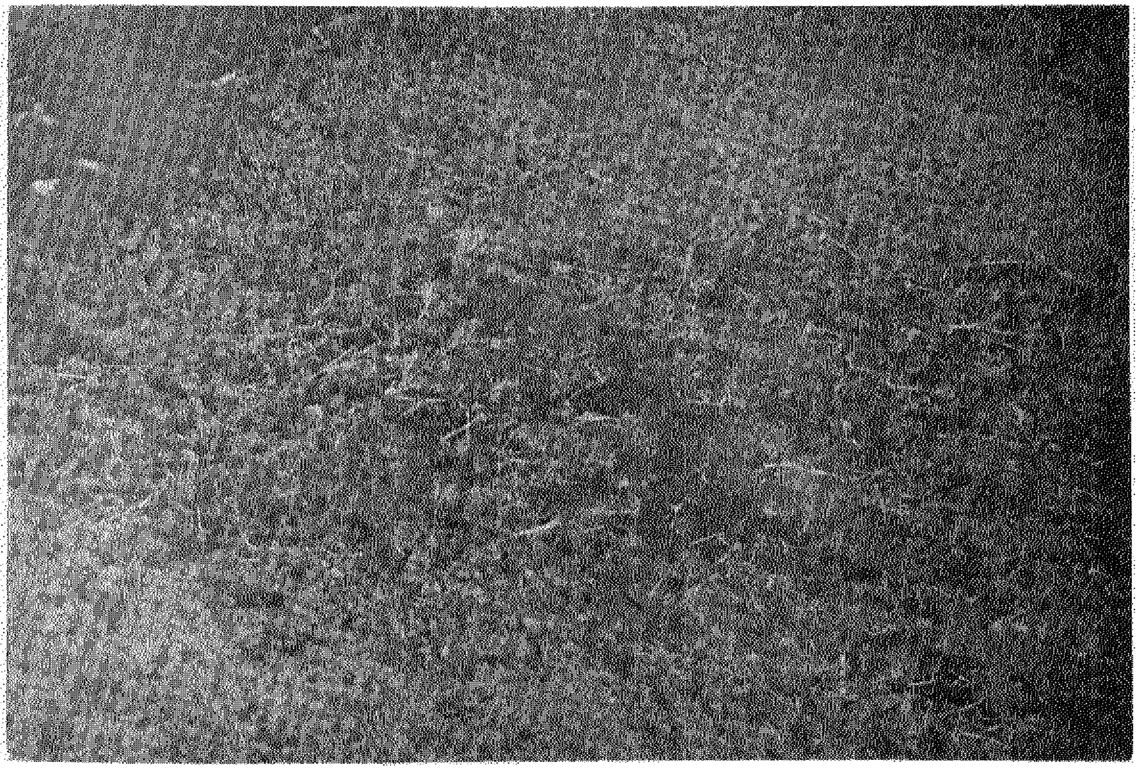


Figure 20. Low altitude, oblique aerial photo within the marsh archipelago coast of Citrus County showing that a number of trees that had been blown down by the storm.

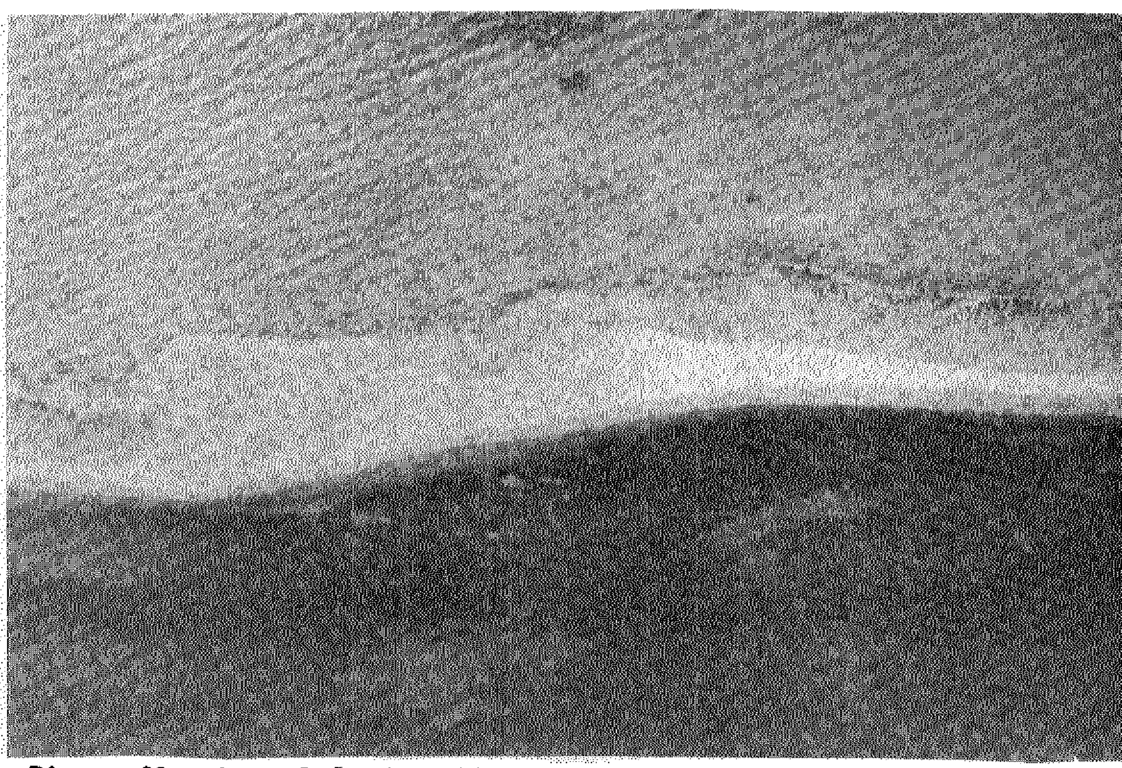


Figure 21. Low altitude, oblique aerial photo of an oyster reef in Crystal Bay. The light area on the crest of the oyster bar resulted from recent transport of oyster shells from storm currents.

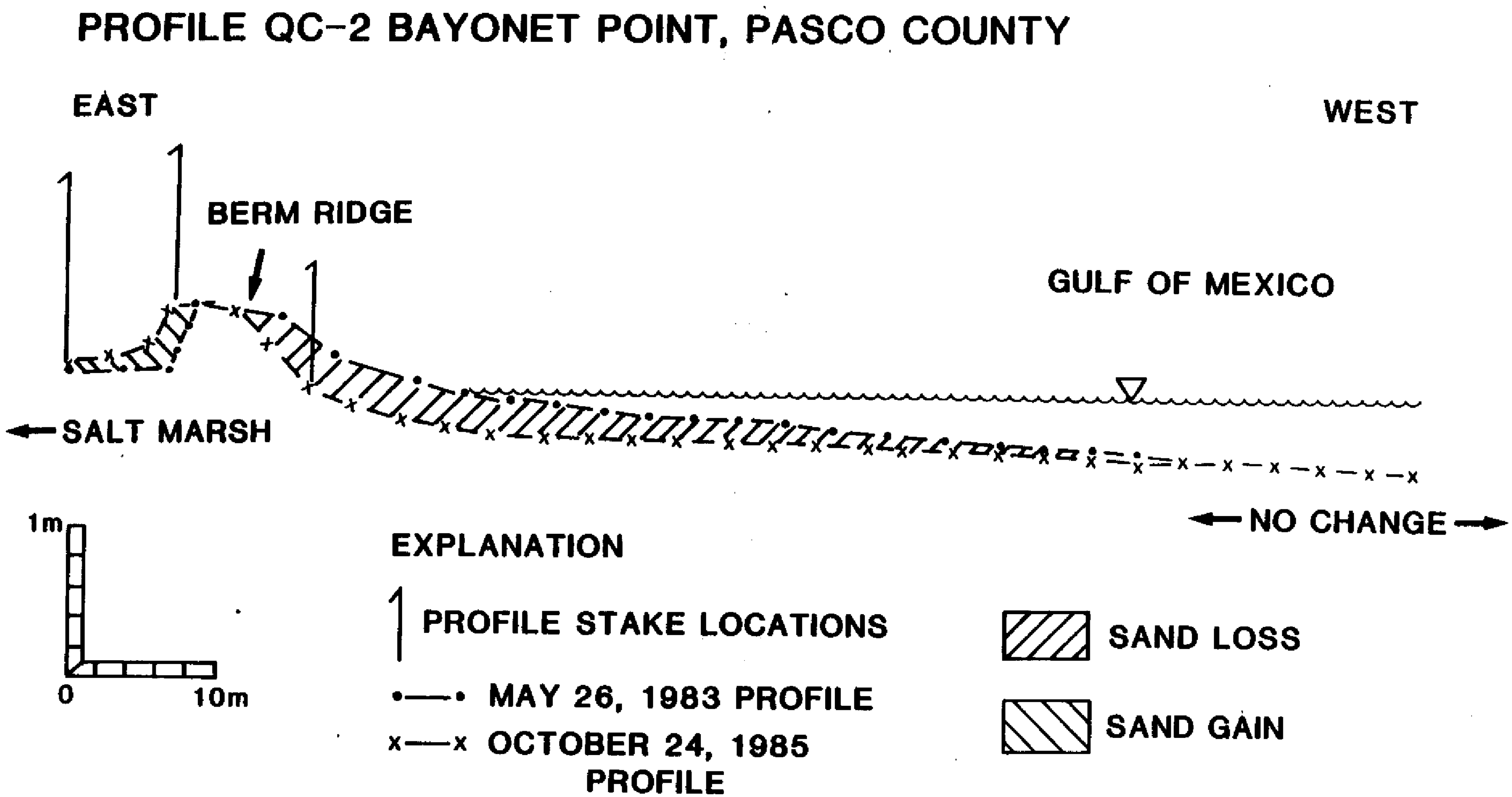


Figure 22. Two topographic beach profiles indicating coastal response to Hurricane Elena at Bayonet Point, Pasco County. Note the lowering of the profile due to sand loss and the landward migration of the berm-ridge. There is no change further seaward. These profiles indicate a net loss of sand. The sand was transferred laterally out of this cross-section. These sediments may have been trapped by nearby tidal creeks which act as small tidal inlets.

CONCLUSIONS

1. Hurricane Elena, a class 3 hurricane (maximum winds 110 knots) came within 81 km of the west-central Florida coast and remained offshore for an unusually long period of time (about 36 hours). Although this storm caused considerable damage to the beach and man-made structures along sandy shorelines to the south, the marsh-dominated coast of Pasco, Hernando, and Citrus Counties suffered relatively little ill effect.

2. There are a number of reasons for the small impact that Elena had on this flat, sand-starved, biologically dominated coast: (1) the storm never made landfall in the study area; (2) the dominant winds were not hurricane force winds along this coast; (3) the winds were directed alongshore; (4) the resulting storm surge was only 2m above MSL; (5) the marsh grasses absorbed wave energy and the plant roots stabilized the substrate; (6) there are numerous rock exposures along this coast; and (7) there are relatively few people and man-made structures to injure or to damage, respectively.

3. There was some shoreline erosion in the Bayonet Point area (7-10m retreat). Marsh grasses were noticeably flattened/matted down; *Juncus* wracks were deposited in the high marsh; several, small overwash fans formed; nearshore sand accumulations were reconfigured; and dead mangrove branches/trunks were broken. However, there was no noticeable change in coastal morphology, no marsh islands disappeared, no oyster bars were eroded, and no marsh hammocks were destroyed.

4. The response of this open-marine, marsh-dominated coast to a major, class 5, hurricane making landfall is still unknown. Such an event could be much more devastating than this coastal response to Hurricane Elena. If sea level is to continue its increasing rate of rise, the marsh coast could approach a state of drowning and be subject to widespread erosion during the 100 year recurring hurricane.

REFERENCES CITED

Balsillie, J.H., 1985, Post-storm report: Hurricane Elena of 29 August to 2 September 1985: Beaches and Shores Post-Storm Report No. 85-2, Florida Department of Natural Resources, Tallahassee, 66 p.

Bodge, K.R., and Kriebel, D.L., 1985, Storm surge and wave damage along Florida's Gulf coast from Hurricane Elena: Department of Coastal and Oceanographic Engineering, University of Florida, Gainesville, 20 p.

Clarke, G.B. and Case, R.A., 1986, Annual data and verification tabulation Atlantic tropical cyclones 1985: NOAA Technical Memorandum, National Weather Service, National Hurricane Center 29, 123p.

Hine, A.C., and Belknap, D.F., 1986, Recent geological history and modern sedimentary processes of the Pasco, Hernando, and Citrus County coastline: west-central Florida: Florida Sea Grant College Publication No. 79, University of Florida, Gainesville, 160p.

Ho, F.P., and Tracey, R.J., 1975, Storm tide frequency analysis for the Gulf coast from Cape San Blas to St. Petersburg Beach: NOAA Technical Memorandum, National Weather Service HYDRO-20, 34 p.

National Oceanographic and Atmospheric Administration (NOAA), 1985, Storm data: National Climatic Center, Asheville, North Carolina, v. 27, no. 9, 47 p.

Price, W.A., 1954, Shoreline and coasts of the Gulf of Mexico: U.S. Fish and Wildlife Service Fishery Bulletin 89, v. 55, p. 39-65.

Tanner, W.F., 1960, Florida coastal classification: Transactions of the Gulf Coast Association of Geological Societies, v. 10, p. 259-266.

U.S. Army Coastal Engineering Research Center, 1973, Shore protection manual, Volume 1: Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 4-180p.

Withlacoohcee Regional Planning Council, 1984, Withlacoochee Hurricane Evacuation Study: 134p.