UFL/COEL-93/001

ANDREW VERSUS HUGO - DAMAGES TO RESIDENTIAL COMMUNITIES

by

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January, 1993

Sponsor:

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University of Florida
Gainesville, FL 32611

REPORT DOCUMENTATION PAGE

1. Report No.	2.	3. Recipient's Accession No.
4. Title and Subtitle Andrew Versus Hugo - Damages to Residential Communities		5. Report Date January, 1993 6.
7. Author(s) Hsiang Wang		8. Performing Organization Report No. UFL/COEL-93/001
9. Performing Organization Name and Address Coastal and Oceanographic Engineering Department University of Florida 336 Weil Hall Gainesville, FL 32611		10. Project/Task/Work Unit No. 11. Contract or Grant No. PD-92-12
12. Sponsoring Organization Name and Address Florida Sea Grant College University of Florida Gainesville, FL 32611		13. Type of Report Final 14.
15. Supplementary Notes		

16. Abstract

Hugo and Andrew were two of the most costly hurricanes to hit the United States in recorded history. They occurred within a time of three years in 1989 and 1992, respectively. The levels of damage were disproportionately high when compared with past hurricanes of comparable strength. Residential communities, in particular, were most severe. This report documents and compares the nature and causes of structural damages inflicted by these two events.

The damage nature was found to be very different. Hugo inflicted very severe water damage on residential structures along the coastal belt spreading over one hundred miles in length. Damage by Andrew, on the other hand, was almost exclusively caused by high wind intensity. Accordingly, the structural damage modes were quite different. A case of reversing the roles of Hugo and Andrew was examined to call attention to the potential hazard of coastal communities.

17. Originator's Key Words Hurricane Andrew Hurricane damage Hurricane disaster Hurricane Hugo		18. Availability Statement	
19. U. S. Security Classif. of the Report Unclassified	20. U. S. Security Classif. of This Page Unclassified	21. No. of Pages 68	22. Price

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TABLE OF CONTENTS

LIST OF FIGURES

Introduction

Andrew and Hugo were two of the most costly hurricanes to hit the United States in recorded history. They occurred within a time span of three years. Hurricane Hugo made landfall on September 21, 1989, just north of Charleston, South Carolina. It claimed more than 40 lives, destroyed over 15,000 homes and caused in upward of $7 billion damage. Hurricane Andrew struck the mainland in the early hours of August 24, 1992, about 25 miles south of Miami. As Andrew passed over the southern tip of Florida, entered into the Gulf of Mexico and regained strength, it made a second landfall south of New Orleans in Louisiana. By early account, the total damage exceeded $20 billion; over 50 lives were lost and in excess of 120,000 homes and commercial structures were demolished. These levels of damage were disproportionately high when compared with the past hurricane losses. The statistics complied in Fig. 1 clearly show the magnitude of the differences.

Of the various aspects of damages caused by the hurricanes, the destruction of residential-type structures was most severe both in terms of cost and human suffering. The characteristics of these two hurricanes were very different as were the nature of structural damages. The post-hurricane responses and actions were also very different. The main purpose of this report is document and compare the nature and causes of structural damages inflicted by these two events in the hope that the collective lesson learned will lead to improving structure survivability in the future. Although the focus of the report is on residential structures other topics such as wind characteristics, beach erosion, storm surge, wave properties and other factors are also presented within the context as cause and effect relationships to structural damages.

The document is based on current available information. Some of the information, particularly related to Andrew will likely be revised in the future when more accurate account becomes available. The building construction industry in the United States mainly uses engineering measurement system (or the English system) such as 2x4 stud, 4x8 sheathing, fastest-mile wind. It would be difficult or at least awkward to use the IM system in this report; therefore, it is decided to retain the engineering units but appended with a unit conversion sheet.

General Description

Buildings and Structures

A total of 14,014 structural units were officially listed as destroyed by Hurricane Hugo at an estimated cost of $700 million. A destroyed structure is defined as one in which the structural damage is greater than 66.67%. Structures sustained lesser degrees of damage clearly far exceeded this number. Most of the damage occurred along a 100-mile or so coastal belt from Folly Beach (south end) to Myrtle Beach (north end). Damage tapered off rapidly beyond this limit although could still be found 30 miles into North Carolina coast. Figure 2 lists the percentage of destroyed structures along this coastal belt. While undoubtedly the combined wind and water forces caused the destruction the latter was the dominant factor. That is, if the wind

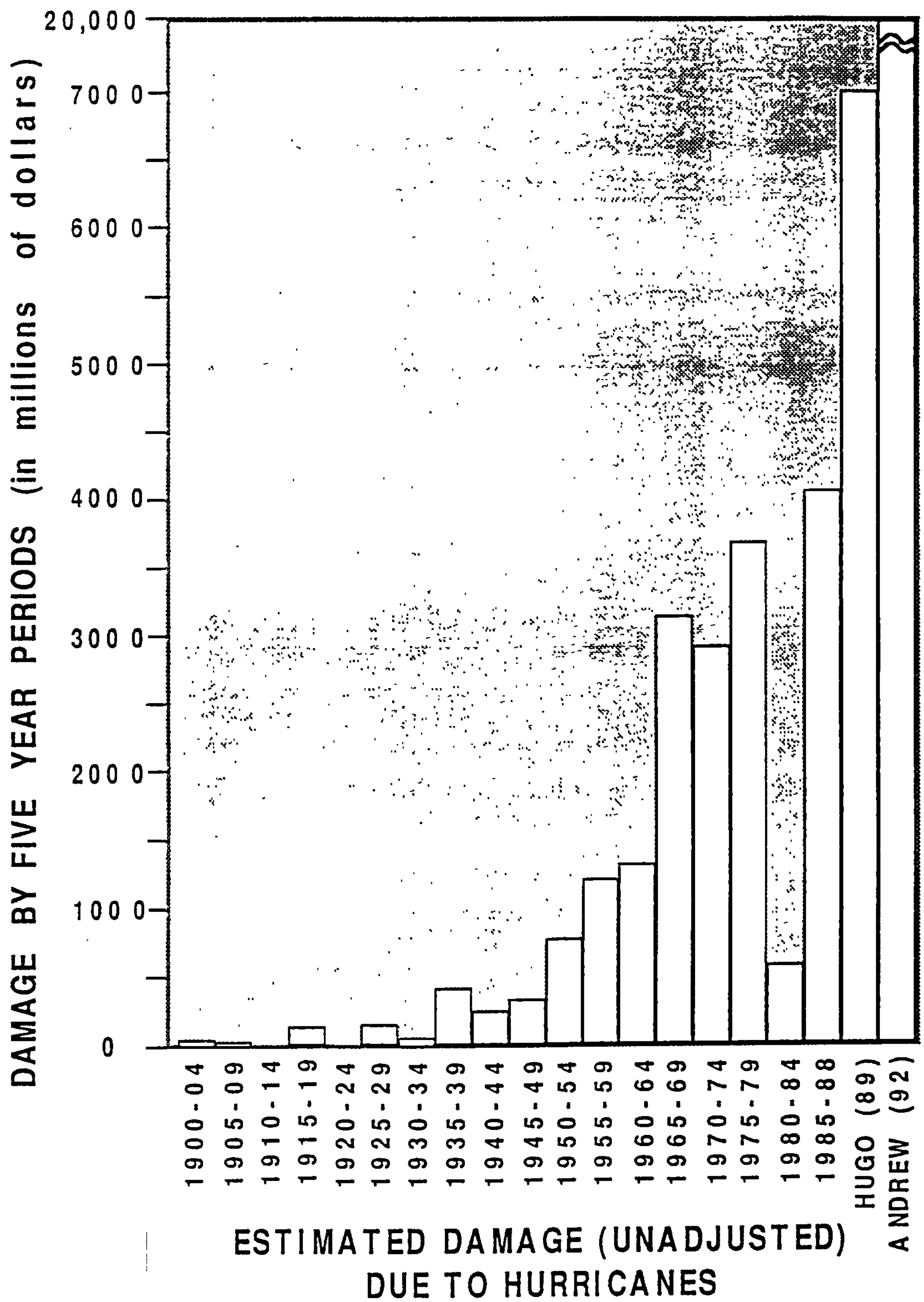

Fig. 1. Summary of estimated damage costs due to hurricanes from 1900-92.

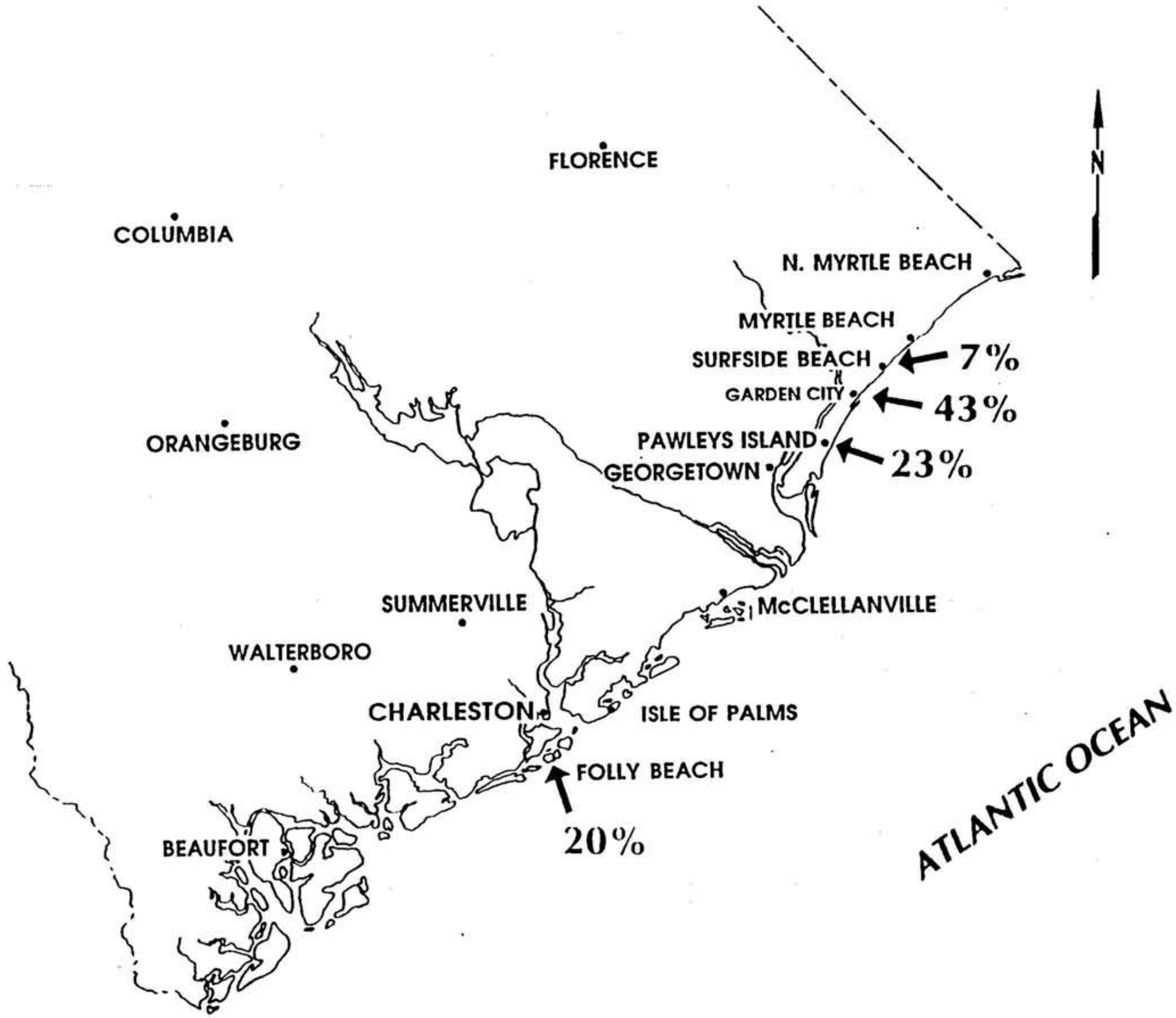

Fig. 2. Percentage of destroyed structures along South Carolina coastal region by Hugo (source of information, South Carolina Coastal Council).

force were absent the damage could be nearly as severe in this coastal belt whereas if the water force were absent the damage could have been considerably lighter. This was evidenced by the fact that just inland of this coastal belt the number of destroyed (not partially damaged) structures, with the exception of mobile homes, were few. Even mobile homes survived just inland of Garden City where the structural damage was most extensive. The spatial distribution of the damage was found to be very uneven in both the coastal belt and inland. Another observed fact was that a significant amount of structural damage in the inland area was caused by fallen trees. The details on the nature of the structural damage along this coast were given by Wang (1990).

By earlier account the destroyed structures due to Andrew were around 63,000 units. The actual number may not be known for a while. This number would put the cost of the destroyed units in the neighborhood of about $3.2 billion (the insurance claims in the affected region were estimated to be about $13.2 billion). The area affected, however, was much smaller than that of Hugo. Heavy damage was concentrated in a 22-mile strip south of Coral Gables shown in Fig. 3. Within this strip, many subdivisions, mobile home parks, condominiums, schools, public buildings, shopping malls and even entire towns could be considered as destroyed. Beyond this strip, damage tapered off sharply. In Kendall and Coral Gables, numerous ripped roofs, signs, uprooted trees and broken window panes were apparent. Destroyed structures by the definition given earlier were few. Also, a few residential and commercial high rises suffered extensive broken glass panels but no structural damage was evident. In Key Biscayne, again, toppled and broken trees were substantial. In the southern end of Key Biscayne which was on the fringe of the maximum wind zone, practically all the Cape Florida park forest was destroyed. However, residential high rises just north of the park entrance sustained very little damage. Single home damages were spotty.

Water damage associated with Andrew was light. There was no reported structural destruction due to dynamic water force. Extensive flooding and inundation in a few waterfront areas were evident including some street flooding. The Burger King Headquarters in Cutler Ridge experienced the highest storm surge of about 17 ft (16.8 ft to be exact) and sustained considerable damage. A few canal residential subdivisions in Cutler Ridge also experienced 1 to 3 ft flooding. In Key Biscayne, a few waterfront developments also suffered flood-related damages of varying degrees. Sand wash over was very light. Several boats, both in Cutler Ridge and Key Biscayne, were washed on land; one actually landed in a swimming pool and another on the main thoroughfare in Key Biscayne.

In south Miami and Miami proper the damage was mainly of the nature of toppled trees, scattered window panes, loss of roof shingles, and fallen signs, utility poles and traffic lights. Damage in Miami Beach, again, was very light. Beyond north Miami, damage was scattered and light, probably comparable to normal storm events.

Unlike Hugo where structural damage occurred almost perpendicular to the hurricane path along a long coast belt, Andrew's damage zone was concentrated in a 22x22 mile square region mainly on the north side of the hurricane track from the landfall location. Figure 4

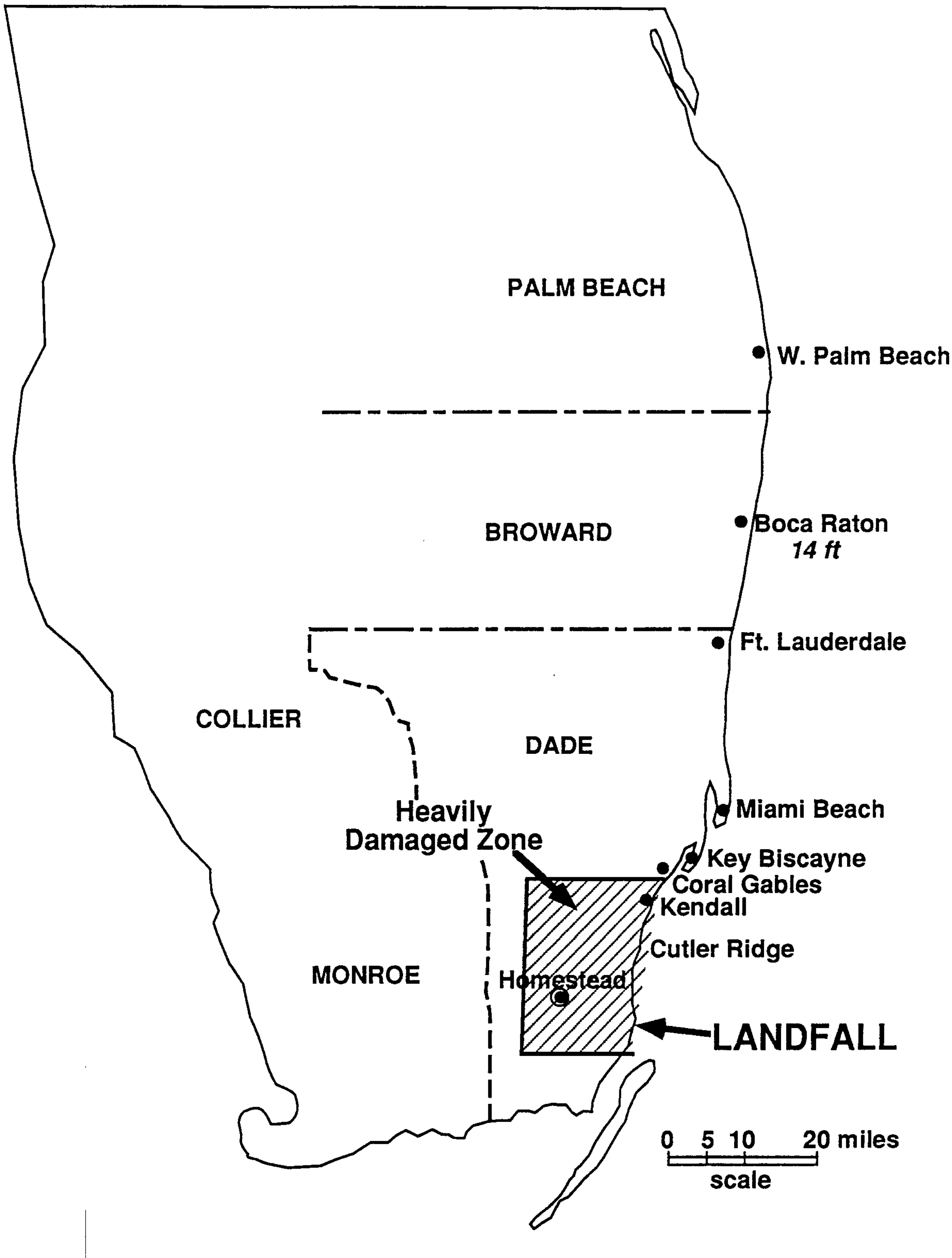

Fig. 3. Zone sustained heavy damage of residential-type structures by Andrew.

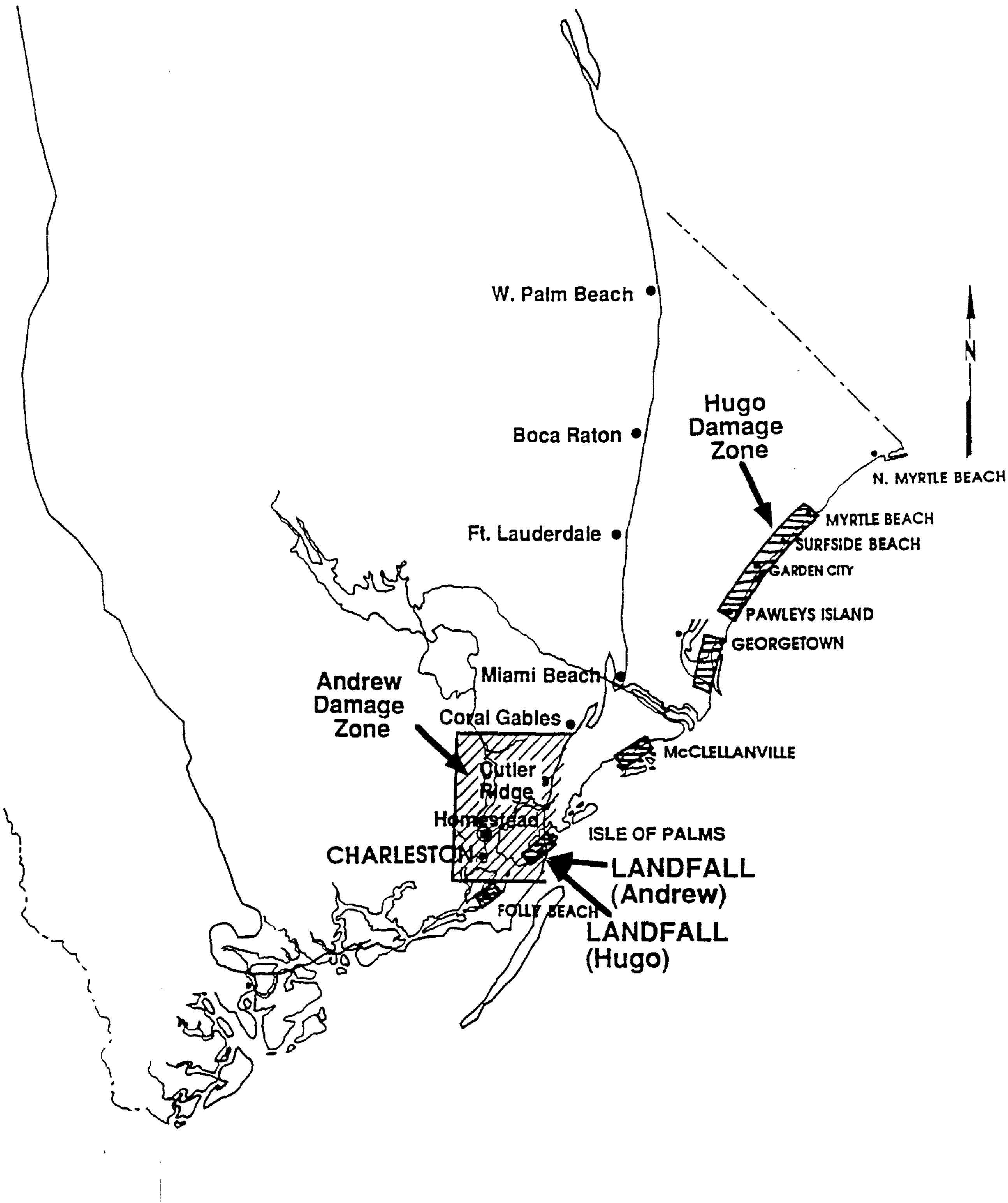

Fig. 4. Comparison of damage zones by Hugo and Andrew.

delineates and compares the sizes and shapes of the damage zones associated with these two hurricanes.

Beaches and Coastal Structures

Hurricane Hugo caused extensive beach erosion along a 140 mile stretch of the South Carolina coast (Stauble et.al 1990). The primary dune line along almost the entire stretch of coast south from Folly Beach to Little River Inlet disappeared, except for a few well-developed dunes on Debidue and Pawleys Island. This sand was transported up to 400 ft inland as overwash, offshore, and alongshore. Figure 5 shows a profile of erosion in Myrtle Beach where the dune loss was 85 ft. Washover was over 2 ft deep in some areas along Surfside Beach (Fig. 6). Debris was everywhere above high tide line. A significant portion of the coastal structures including wooden and concrete seawalls, stone revetments, wooden and stone groins was heavily damaged or completely destroyed. Stones from revetments were thrown around by waves, breaking sliding doors and windows or even walls.

By contrast, Hurricane Andrew had very little effect on beaches and waterfront structures, both buildings and coastal protective structures. Post beach survey showed little or no beach erosion in Miami Beach and beaches in Key Biscayne except heavy debris lines along high tide mark (Fig. 7). Street washover was negligible. No significant coastal structure damage has been attributed to Andrew except the artificial reef just recently installed offshore West Palm Beach for coastal protection. This artificial reef was made of concrete blocks; some of which were reported as sinking into the sand from post-storm survey.

Hurricane Track and Wind Field

In order to associate damages to a specific hurricane we must have some appreciation of a hurricane wind field. The wind field and the track of Hugo were fairly well documented (see Powell and Black, 1990, for instance). The wind field of Andrew also became available in various news accounts and in the preliminary report published by National Hurricane Center (NHC, 1992). Figure 8 shows the tracks of both Hugo and Andrew and the dates of reaching various wind stages. Hugo was clearly a much larger system partly because it had already reached hurricane strength almost 8 days prior to landfall. During this 8-day period the perimeter of influence expanded considerably. Therefore, at the time of landfall, wind speed at hurricane level (73 mph) reached as far as 200 miles from the eye. Andrew, on the other hand, developed into a hurricane in the morning of August 22 only 2 days before landfall, thus, lacked time to expand its influence parameter. A high pressure system in the Atlantic just north of the hurricane track also helped to compact the wind field. Therefore, by estimation, wind speed at hurricane level extended to about 60 miles from the eye, or only about one-third of Hugo.

The maximum sustained surface wind (1-minute average at instrument height) was generally quoted as equal to 145 mph for Andrew with a corresponding radius of maximum wind of 11 miles. The central pressure was determined to be around 930 mb, or 27.47 in Hg (with

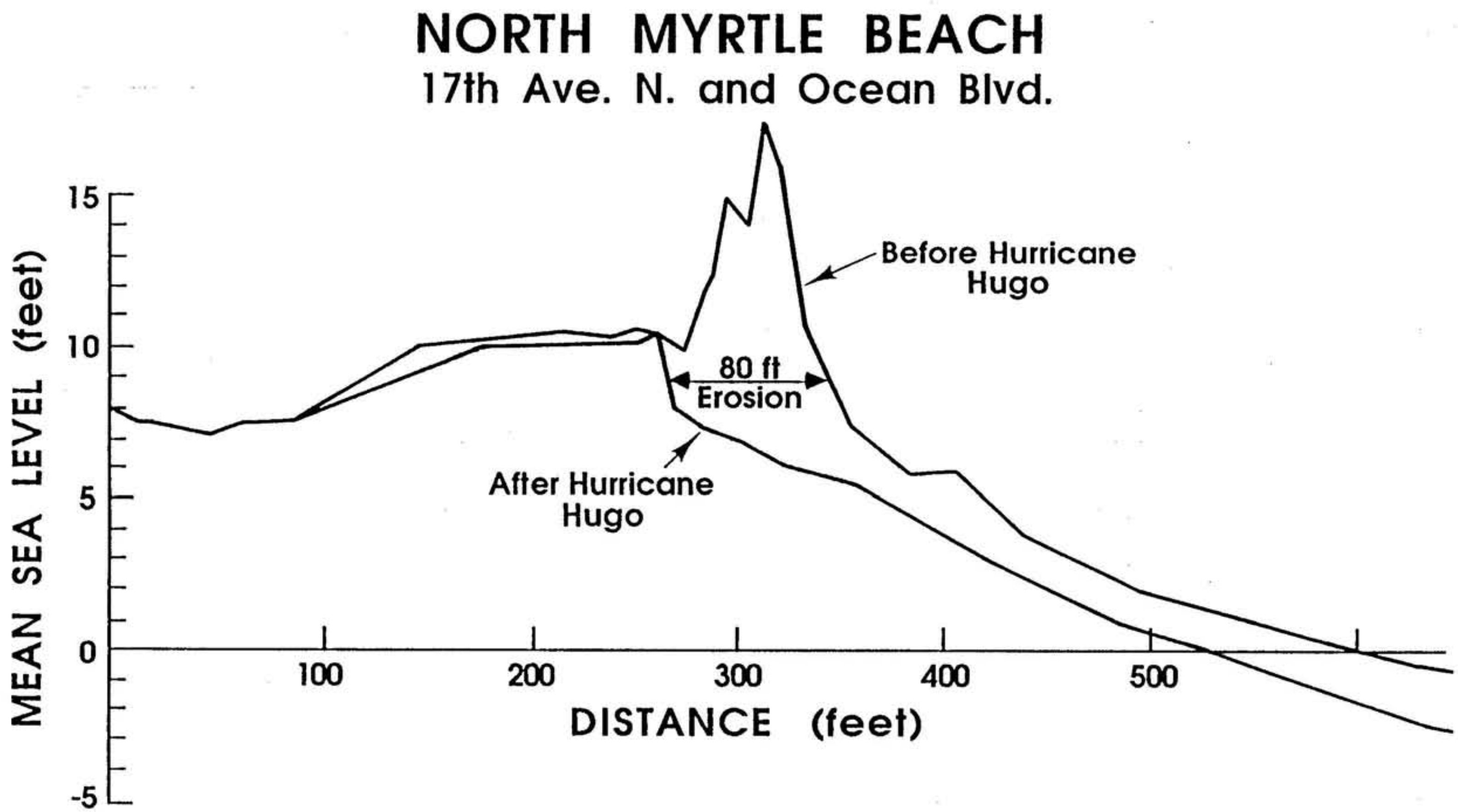

Fig. 5. An example of beach erosion profile in Myrtle Beach due to Hugo.

Fig. 6. Sand washover over 2 ft deep along Surfside Beach.

Fig. 7. Andrew caused little or no beach erosion. Heavy debris line is the common sight along the beaches.

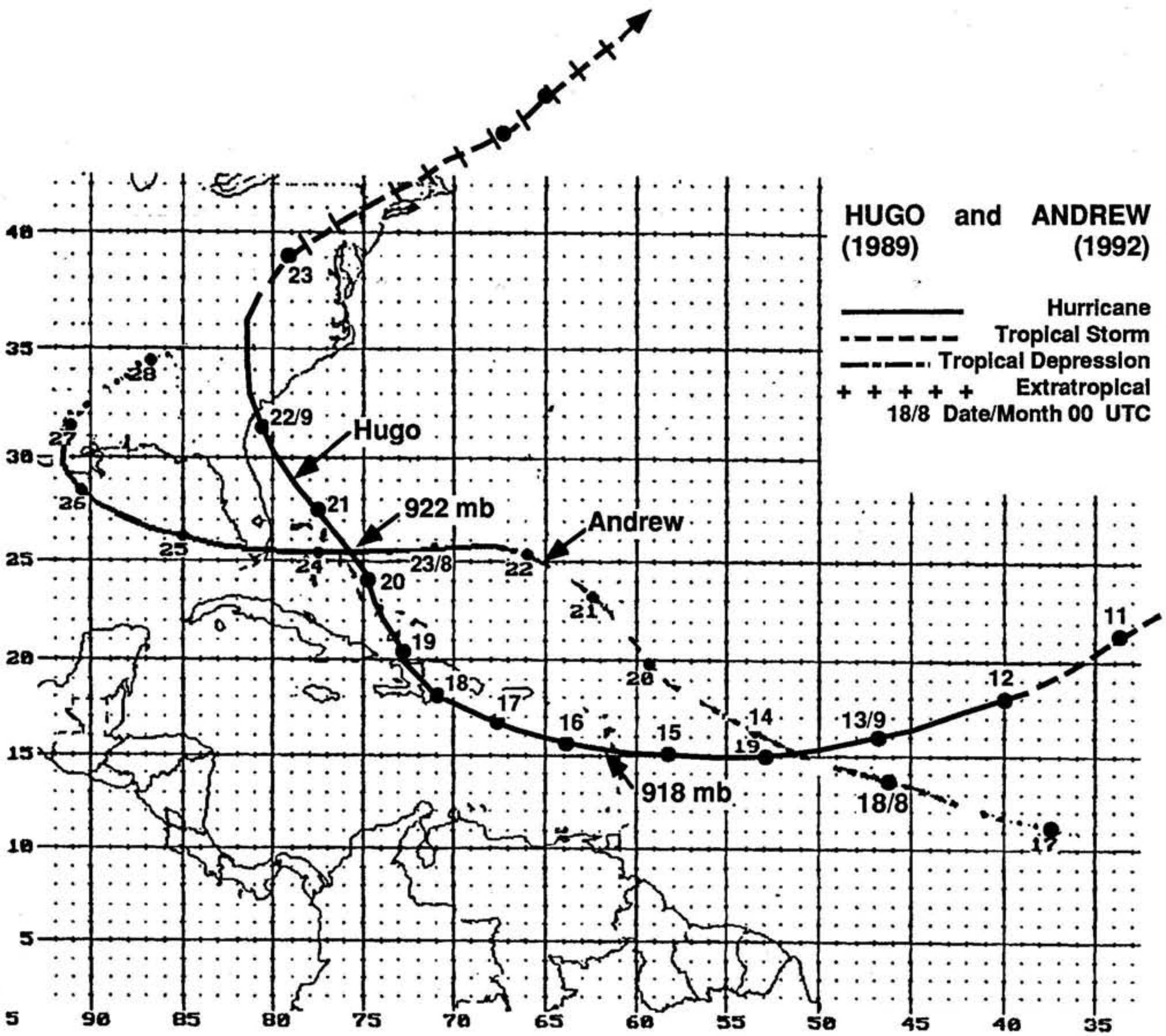

Fig. 8. Hurricane tracks of Hugo and Andrew.

verified aircraft measurement of 932 mb one hour prior to landfall and unofficial surface observations of 926 mb (NOAA, 1992). The ambient pressure was difficult to determine precisely and was suggested by NHC to be around 1014 mb, or 30 in Hg. The wind field of Hugo can be found from Powell and Black (1990). The maximum wind was determined to be 135 mph with a corresponding radius of about 15 miles. The actual measured maximum wind at the ground, however, was only 87 mph owing to the fact that there was no instrument in the high wind zone. The central pressure at landfall was 934 mb, slightly higher than Andrew. The ambient pressure, however, should be slightly lower than Andrew on the order of 1009 mb. In terms of wind strength and based on Sirfir Simpson scale, both hurricanes were classified as category 4 during landfall. Table 1 provides the Sirfir Simpson wind intensity scale together with storm surge level scale as specified by FEMA (Federal Emergency Management Administration). The wind speed and surge level are not always compatible. Therefore, a hurricane could be a category 4 in terms of wind strength but only category 3 in storm surge level or vice versa. This storm surge level will be discussed in the next Section. In terms of return period, the often used statistic is the hurricane central pressure. The cumulative frequencies of hurricane central pressure were complied for 4 zones along the eastern seaboard of the United States by NHC. These cumulative frequencies in these 4 zones are given in Fig. 9 together with a map delineating the boundaries of the zones. As can be seen Andrew made landfall in zone 1 and Hugo hit the boarder between zone 2 and zone 3. Based upon central pressure, both Andrew and Hugo can be classified as 25-year hurricanes in zone 1 and 100-year hurricanes in zone 2 or 3.

Table 1: SAFFIR/SIMPSON HURRICANE SCALE

Scale	Central Pressure (millibars)	Wind Speed m/s	Wind Speed mph	Surge m	Surge ft
1	≥ 980	33-42	74-95	1.2-1.5	4-5
2	965-979	43-49	96-110	1.6-2.4	6-8
3	945-964	50-58	111-130	2.4-3.7	9-12
4	920-944	59-69	131-155	3.8-5.5	13-18
5	< 920	> 69	> 155	> 5.5	> 18

Using the available pressure information given by NHC, idealized wind fields of Hugo and Andrew at landfall were created. Figure 10 compares the cross-sections of the wind fields corresponding to these two events. The values given in this figure represent sustained wind (1 minute average) at 10 M (33 ft) elevation. As can be seen Andrew was more intense but considerably smaller than Hugo. For instance, the zone exceeding 90 mph covered only a 45-mile strip for Andrew but more than double that for Hugo.

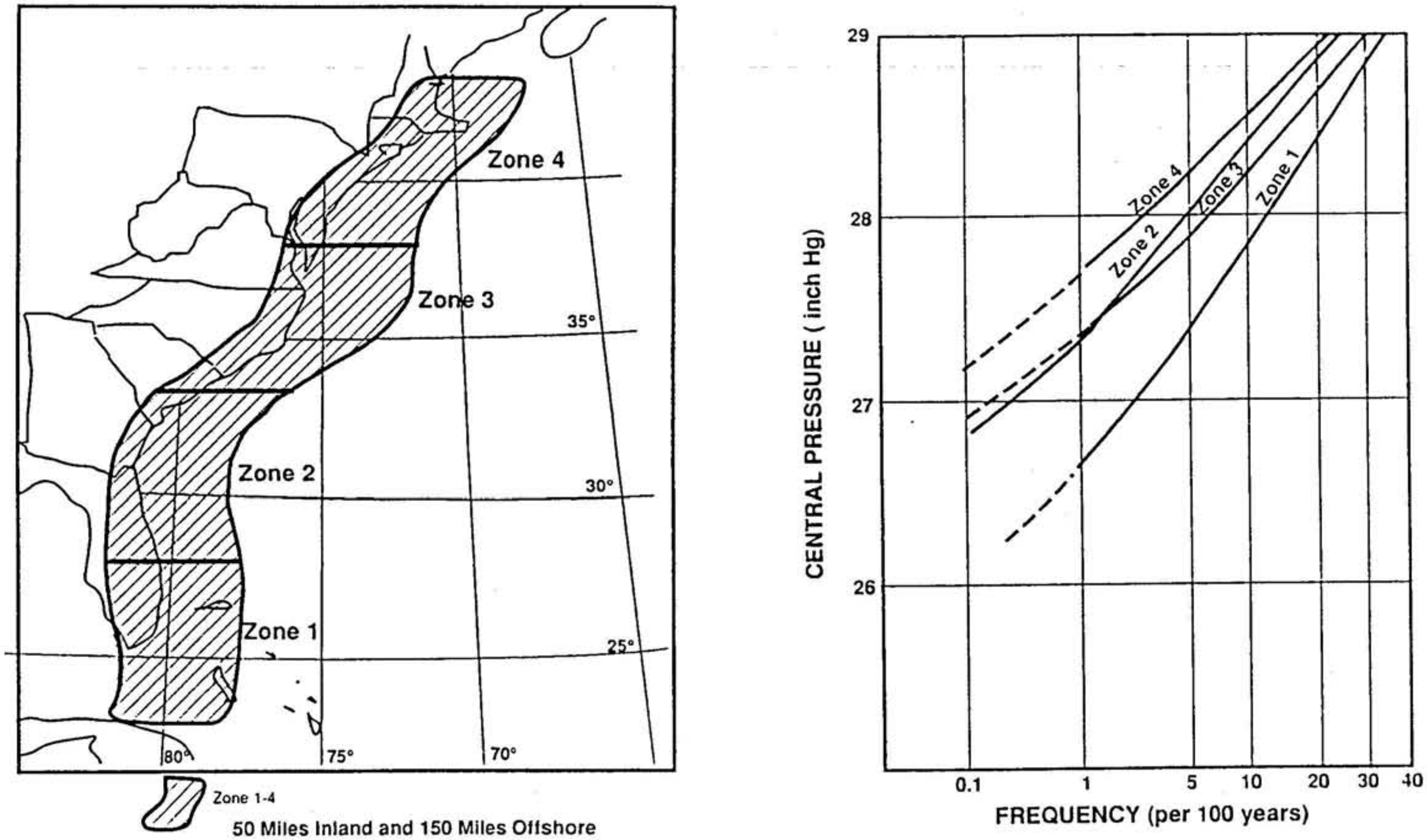

Fig. 9. Cumulative frequencies of hurricane central pressure.

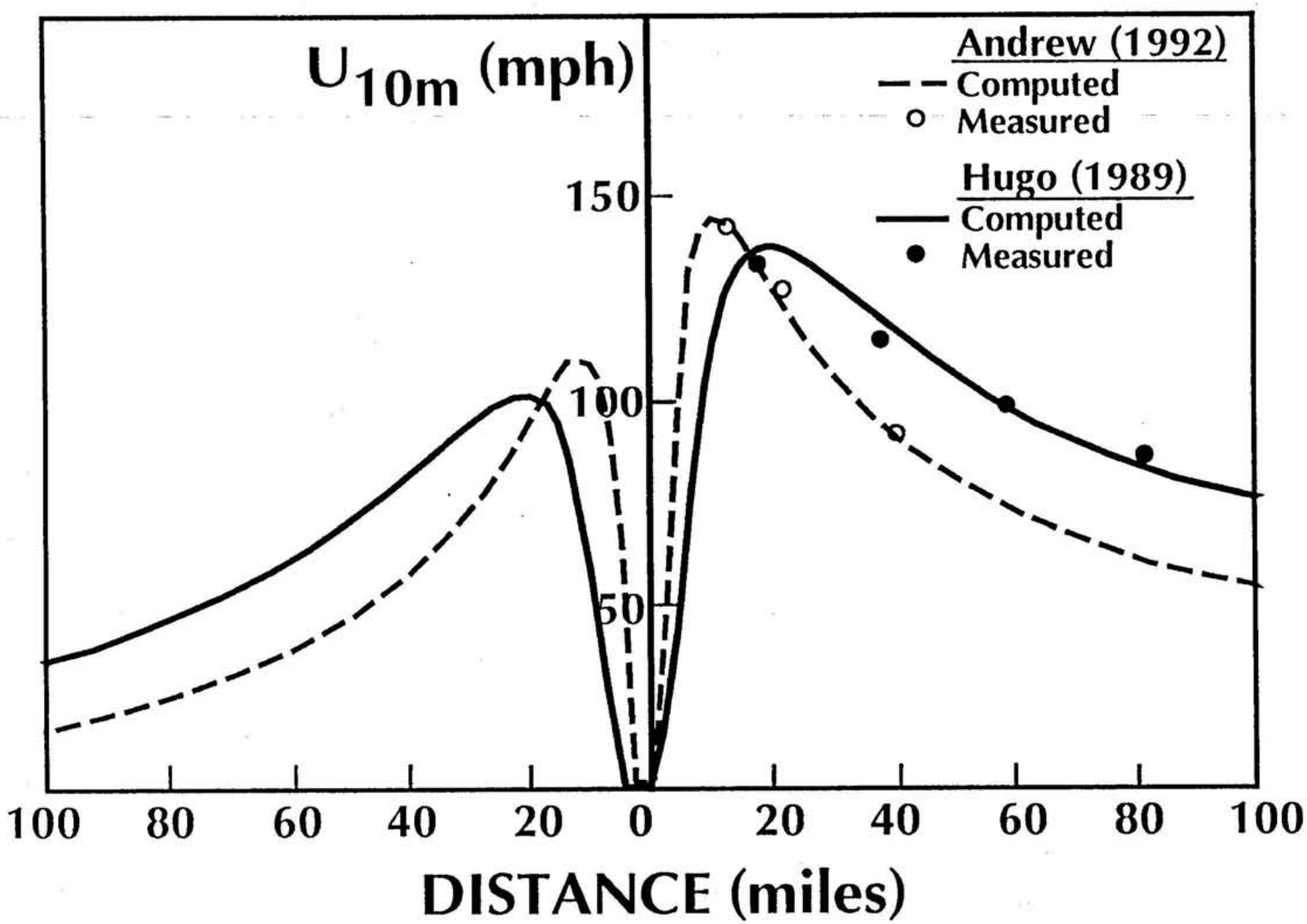

Fig. 10. Hugo and Andrew wind cross-section comparisons.

The overland wind strength contours can be constructed if the rate of decay is known. This decay rate is influenced by the meteorological factor as well as ground surface characteristics. For Hurricane Hugo, the rate of pressure rise was established at 6 mb/hr (Powell and Black 1990). For Hurricane Andrew the central pressure also rose right after landfall before dropping again as it re-entered the water. By extrapolating the pressure data between 8/24/0000 to 8/24/1200 published by NHC, the rate of pressure rise was estimated on the order of 2 - 2.5 mb/hr during the overland period. This decay rate is slower than Hugo but closer to the average rate of recorded hurricanes. Idealized overland wind fields after landfall were then created following the hurricane tracks. They are given in Figs. 11 and 12 for Hugo and Andrew, respectively. The values are sustained wind at 10 m elevation. For Hugo, the zone of maximum wind intensity defined here as exceeding 130 mph was rather small and was over a sparsely populated forestry area. The major population center of Charleston is on the left of the hurricane track in the 90-120 mph influence zone. However, owing to the associated large wind field the 75 mph zone covered a horizontal distance over 100 miles along the coast at the landfall and extended beyond Myrtle Beach into North Carolina boarder. For Andrew, the wind speed was higher and a zone of wind intensity exceeding 140 mph existed. This zone almost coincided with damage zone shown in Fig. 2. Unlike Hugo, the wind strength decayed rapidly from the center. Miami, for instance, was already in the 90-120 mph zone, comparable to Charleston in Hugo.

Storm Surges and Waves

Storm surges and waves are two major causes of waterfront structure damage and beach erosion. Both hurricanes made landfall at high tide compounding the rise of water levels.
For Hugo, the storm surges and highwater levels were fairly well documented by a number of agencies. Figure 13 shows the highwater marks from the Federal Insurance Administration and the associated level of damages along the South Carolina coast. Garcia, et.al. (1990) also compiled and published the measured highwater level elevations from Kiawah Island to Winyah Bay as shown in Fig. 14. These two values were in general agreement; some differences did exist owing to probably local influences. On the basis of these data, the highest water mark was put at 20.2 ft. Andrew's highwater mark surveys were not complete at this moment. The preliminary storm tide height results along western shore of Biscayne Bay as published by the U.S. Geological Survey are also given in Fig. 14. The maximum value was given as 16.9 ft off Cutler Ridge. The surge level tapered off rapidly towards both sides. On the south end of Key Biscayne in the Cape Florida national park, the highwater level was determined to be 9.4 ft. At north end of Miami Beach, a tide gage recorded highwater level of 6.0 ft with respect to MLLW on August 24, 5:15 EDT. This is the only location where the water level time series is available. The storm surges induced by Andrew were less than that by Hugo, both in terms of magnitude and duration, and affected a much smaller area.

There was no measured wave data in either hurricane. To date, there has been no serious attempt to estimate the wave conditions associated with them. Yet, different wave conditions were clearly one of the major reasons why these two hurricanes caused markedly different beach erosion and waterfront damage. There were many postulations including the influence of

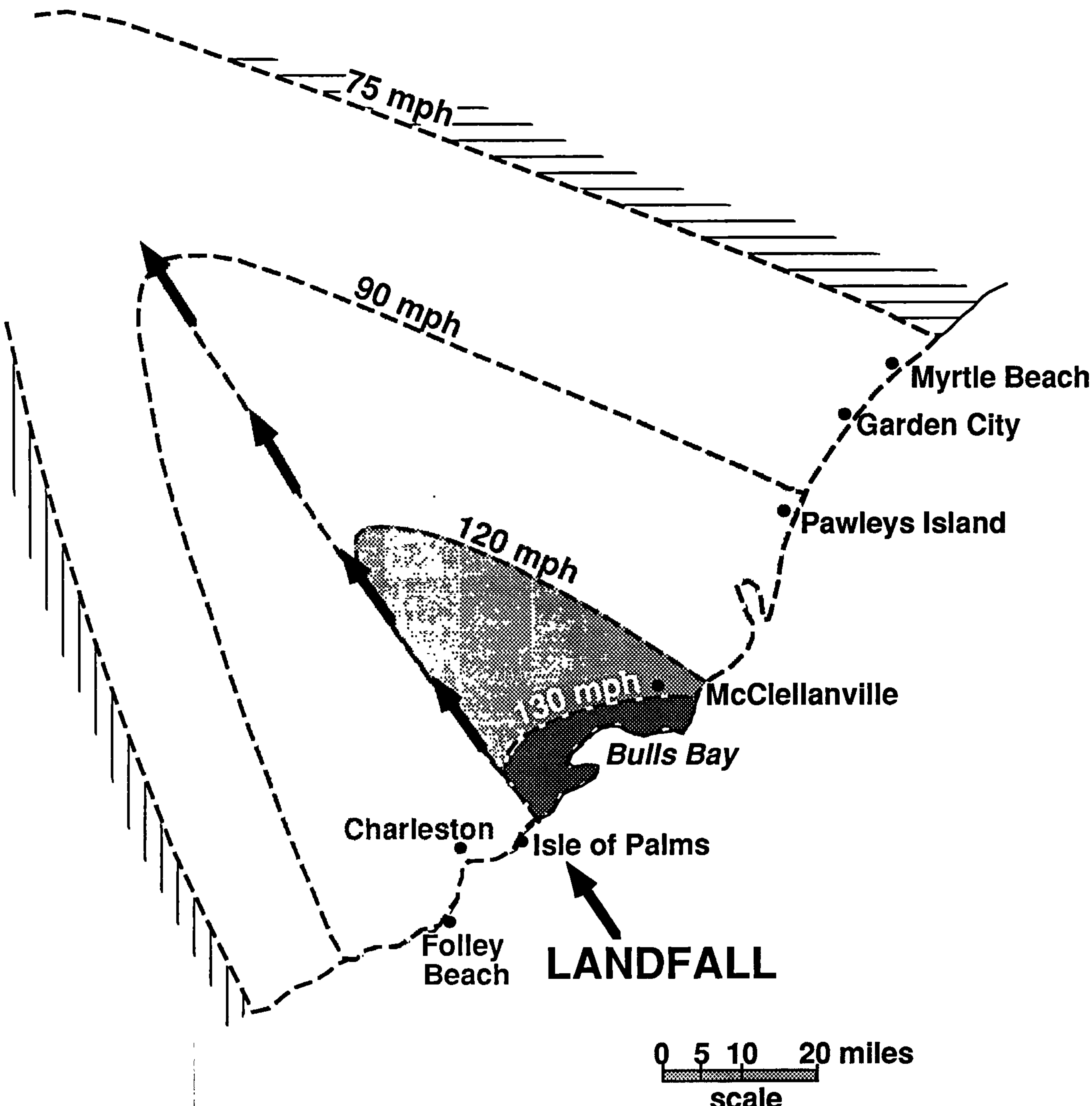

Fig. 11. Wind intensity contours of Hurricane Hugo.

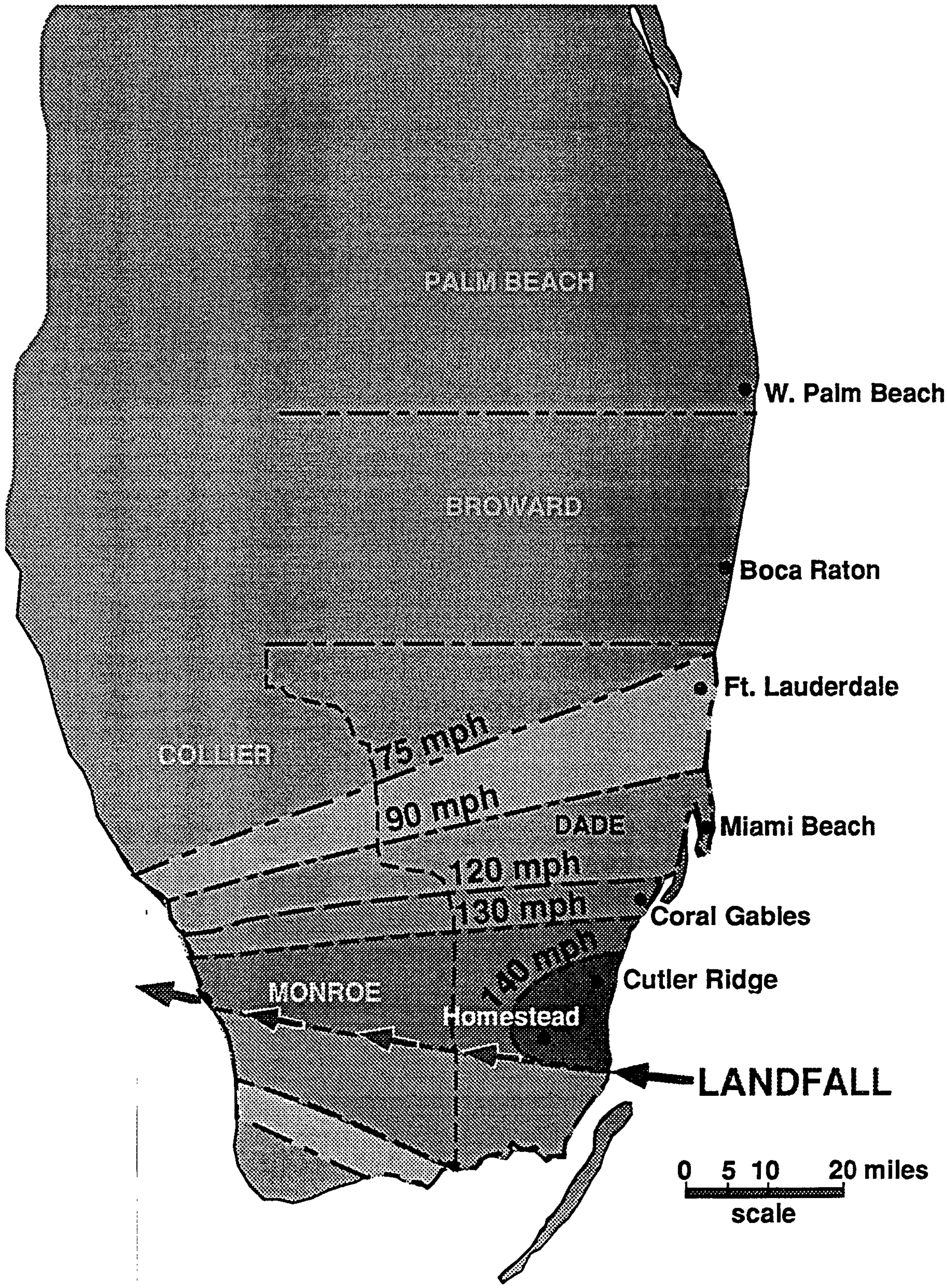

Fig. 12. Wind intensity contours of Hurricane Andrew.

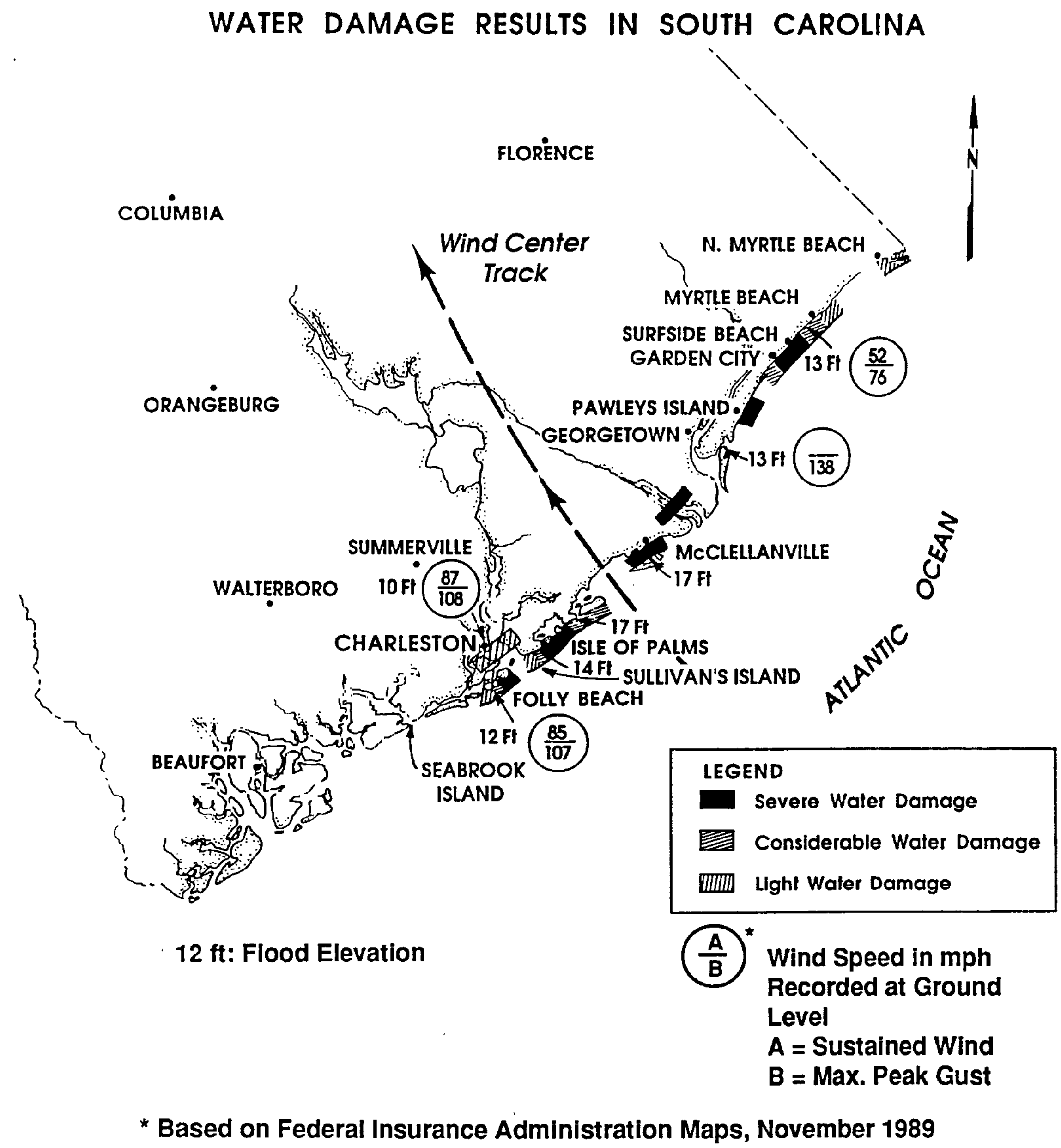

Fig. 13. Highwater marks and general damage assessment along S.C. coast under the influence of Hugo (surge and wind information from Federal Insurance Administration, 1989).

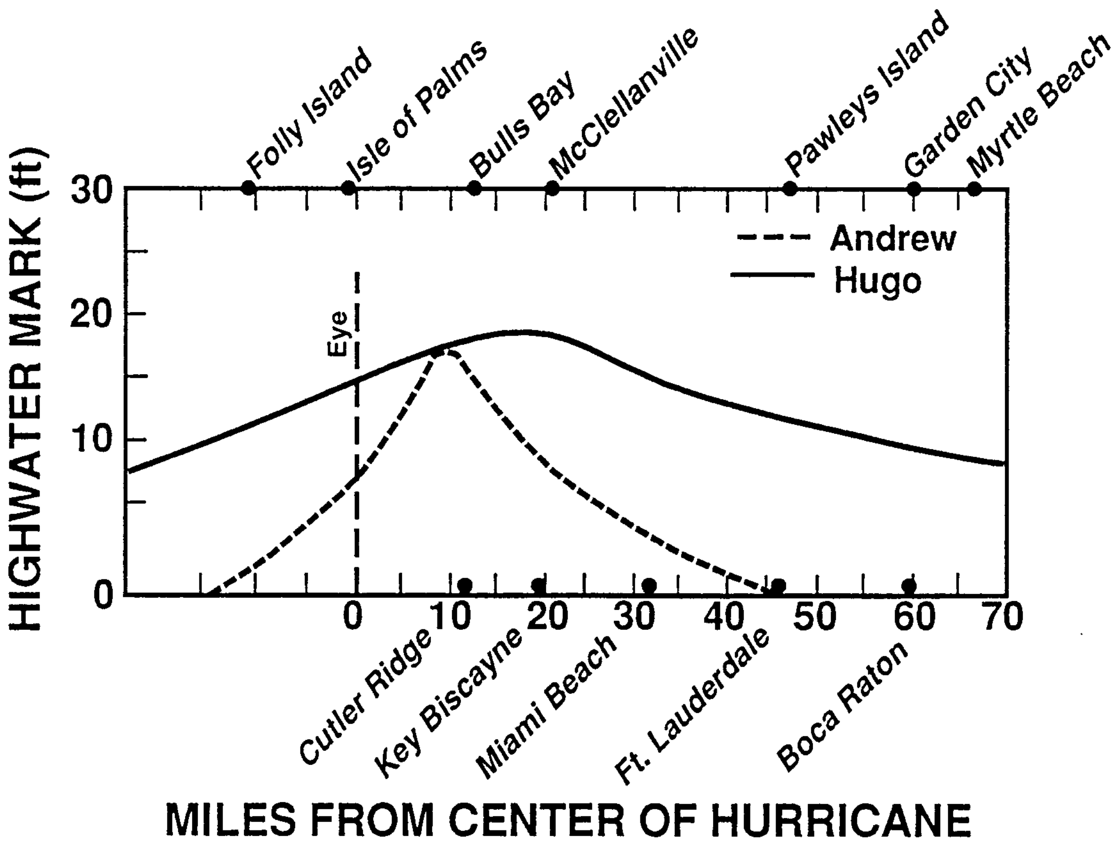

Fig. 14. Highwater elevations due to Hugo (from Garcia, et. al. 1990) and due to Andrew (from U.S.G.S., 1992).

Bahamas Banks, better nourished beaches, etc., as reasons for the light beach damage in Andrew. In an attempt to shed more light on this aspect, wave fields were generated here based on the wave hindcast model developed by Lin (1988) using simplified hurricane wind fields as input. Wave fields corresponding to three wind fields were generated:

1. Hurricane wind field of Andrew.
2. Hurricane wind field of Hugo.
3. Hurricane wind field of Hugo following the track of Andrew.

Figures 15 to 17 show, respectively, the computed significant wave height distributions on August 22, 19:00 (Andrew reached hurricane strength), August 24, 06:00 (Andrew made landfall) and August 24, 21:00 (12 hrs after landfall). The sheltering effect of Bahamas Banks is clearly revealed in these figures as high waves are being diverted towards northwest direction when the hurricane center is east of the Bahamas Bank, during its most potent wave generation stage. As the hurricane passes over the Bank the effective fetch becomes limited, thus, limiting the growth of local wave height. Figures 18 to 19 show, respectively, the time history of wave growth and decay at Miami Beach and West Palm Beach. The sheltering effect is seen to be

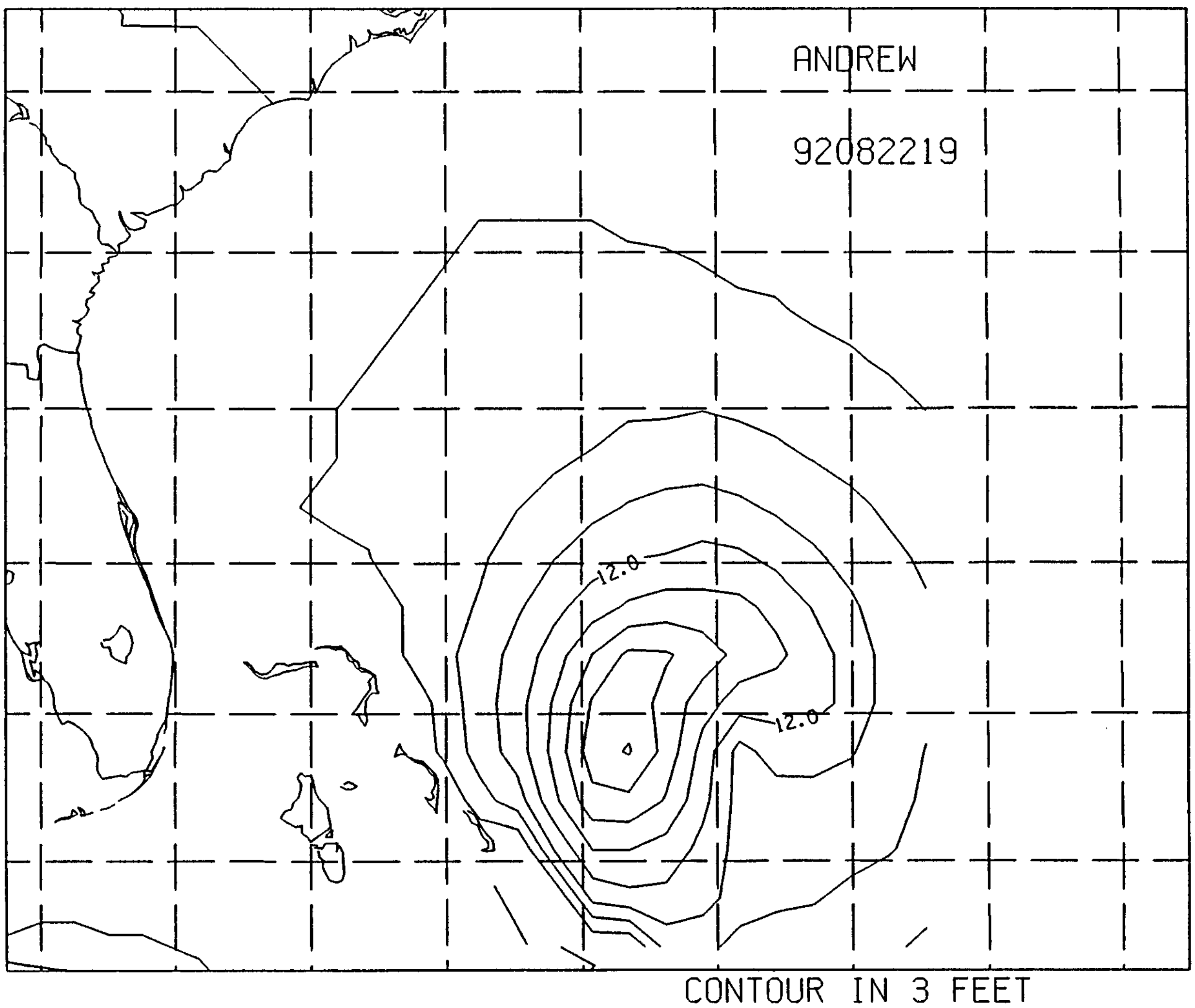

Fig. 15. Computed wave height distributions when Andrew reached hurricane strength on Aug. 22, 19:00 hrs.

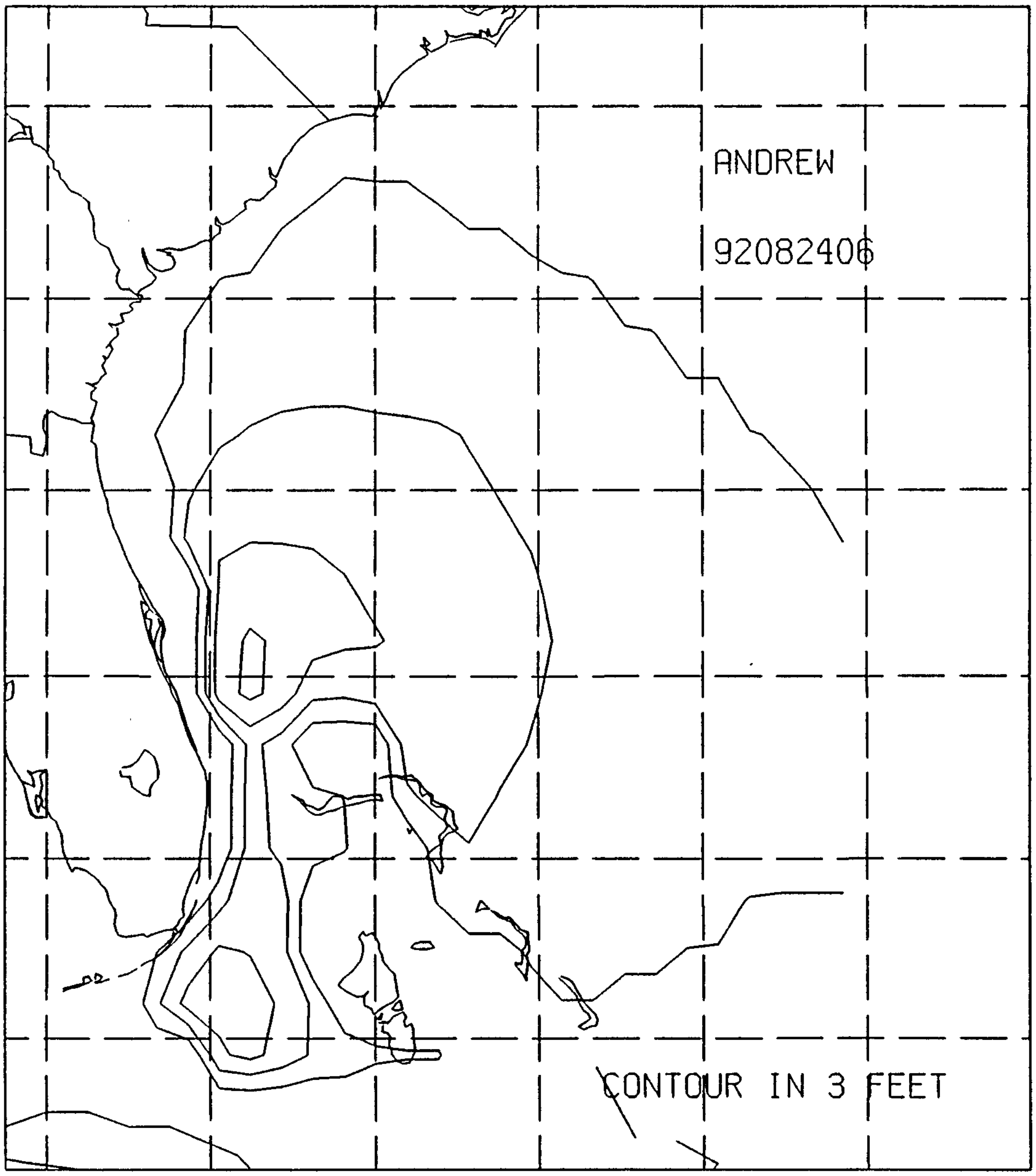

Fig. 16. Computed wave height distributions when Andrew made landfall on Aug. 24, 06:00 hrs.

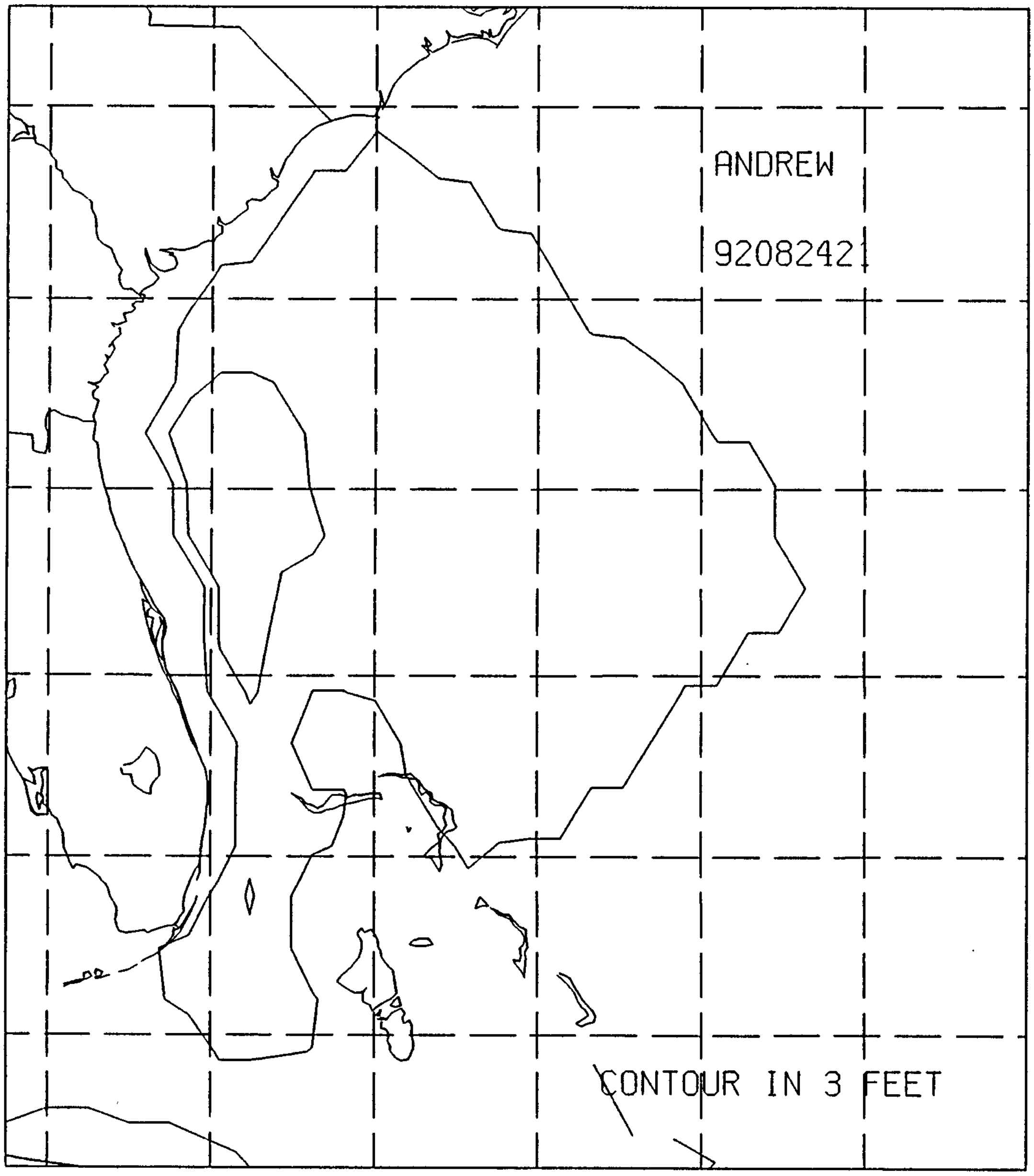

Fig. 17. Computed wave height distributions 12 hrs. after landfall on Aug. 24, 21:00 hrs.

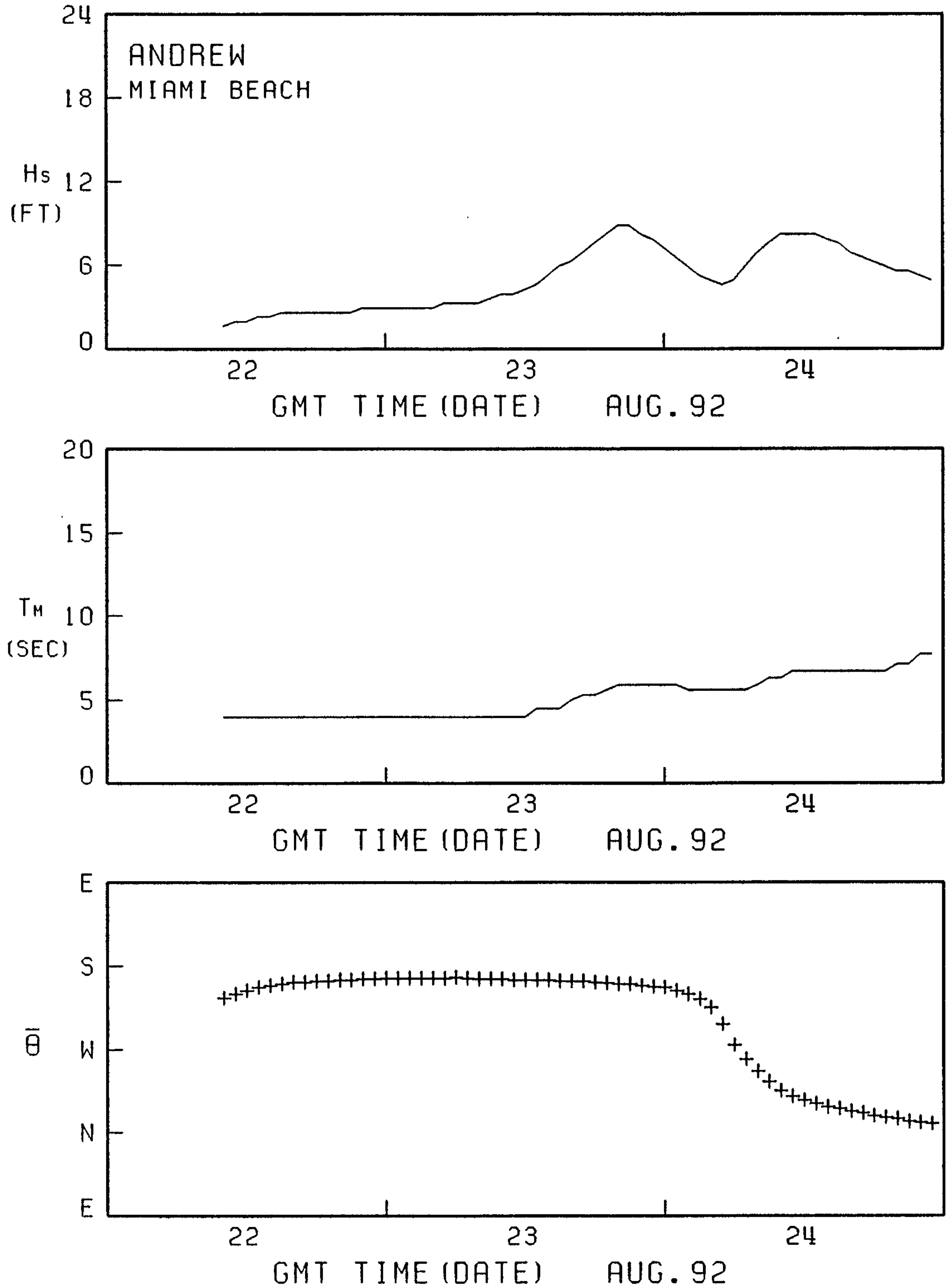

Fig. 18. Computed time history of wave height at Miami Beach, FL. during Andrew.

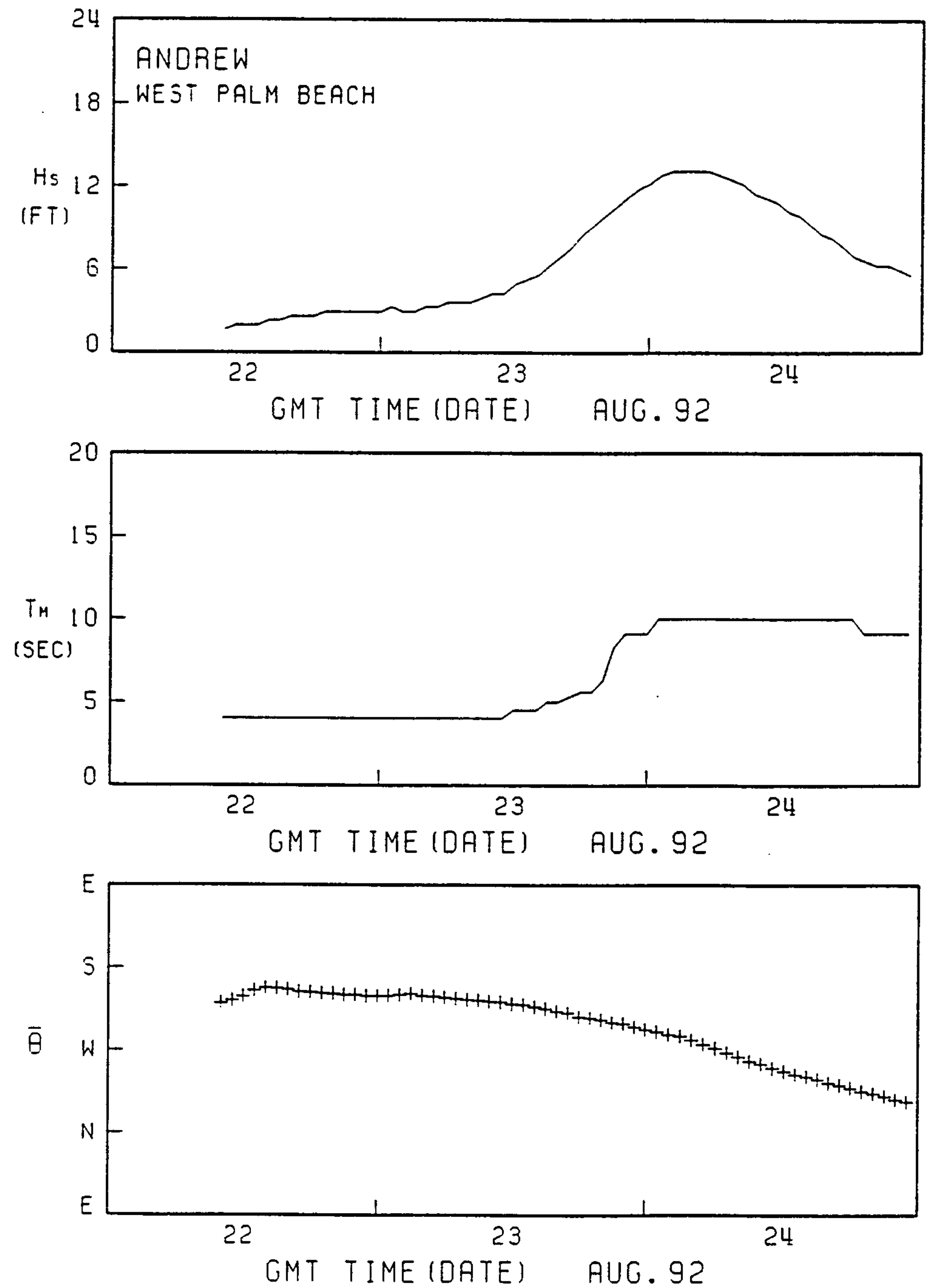

Fig. 19. Computed time history of wave height at West Palm Beach, FL. during Andrew.

strong at Miami Beach. Here, wave height peaks to around 8.5 ft about 10 hours prior to landfall, then drops to 5 ft at landfall. The wave height picks up again after landfall to about 8.0 ft before falling back. Overall, the duration of high waves is rather short, about 18 hrs for waves over 6 ft or higher, for instance. The wave directions for most of the time are towards south (prior to landfall) or north (after landfall) which spares Miami Beach from direct wave pounding. These favorable factors are further aided by the fact that at the peak of the surge (around 5 am EDT, August 24) the wave height dips to a low of 4.5 ft. At West Palm Beach, waves are considerably higher (with maximum about 13 ft), duration of high wave attack is longer and the wave angles with respect to shore-normal are smaller. All of them contribute to a more potent environment.

Figures 20 to 22 show, respectively, the significant wave height distributions generated by a Hugo wind field prior to landfall, during landfall and after landfall. Figures 23 to 25 give the time history off Charleston (south end), Pawleys Inland (center) and Myrtle Beach (north end), respectively. From these figures, one can see that the wave field generated by Hugo is considerably larger and the wave height much higher than that by Andrew. The peak wave heights are over 20 ft off Charleston and Myrtle Beach which are 100 miles apart and are even higher in between them such as shown off Pawleys Inland. Since the power of destruction on sandy beaches can be roughly measured in terms of wave height to the 2.4 power ($H^{2.4}$), waves produced by Hugo are 10 times as potent as that by Andrew in beach erosion.

It should be noted that the wave conditions presented here are not hindcast but are computed utilizing idealized hurricane wind as input.

Damage Modes

On the basis of post-damage surveys of Hugo and Andrew, the structural damage modes most commonly observed as well as the factors that critically affect the structural performance are discussed here. The causes of damage can be roughly divided as water- and wind-related. As we have shown in the previous sections, damage associated with Hugo was predominantly due to water-induced forces whereas the destruction in Andrew was almost exclusively caused by high winds.

Water Forces and Associated Damage Modes

In hurricane events, water forces are mainly induced by storm surge and water waves. Although rain fall could also spawn significant damage by inducing stream flooding or through damaged roofs and windows, it usually does not constitute a direct destructive force to structures.

Storm surge is water level rise above the normal as a result of wind stress and low pressure associated with hurricane passage. Although the name of storm surge has the connotation of a dynamic nature the force induced by it can be treated, more or less, as a steady

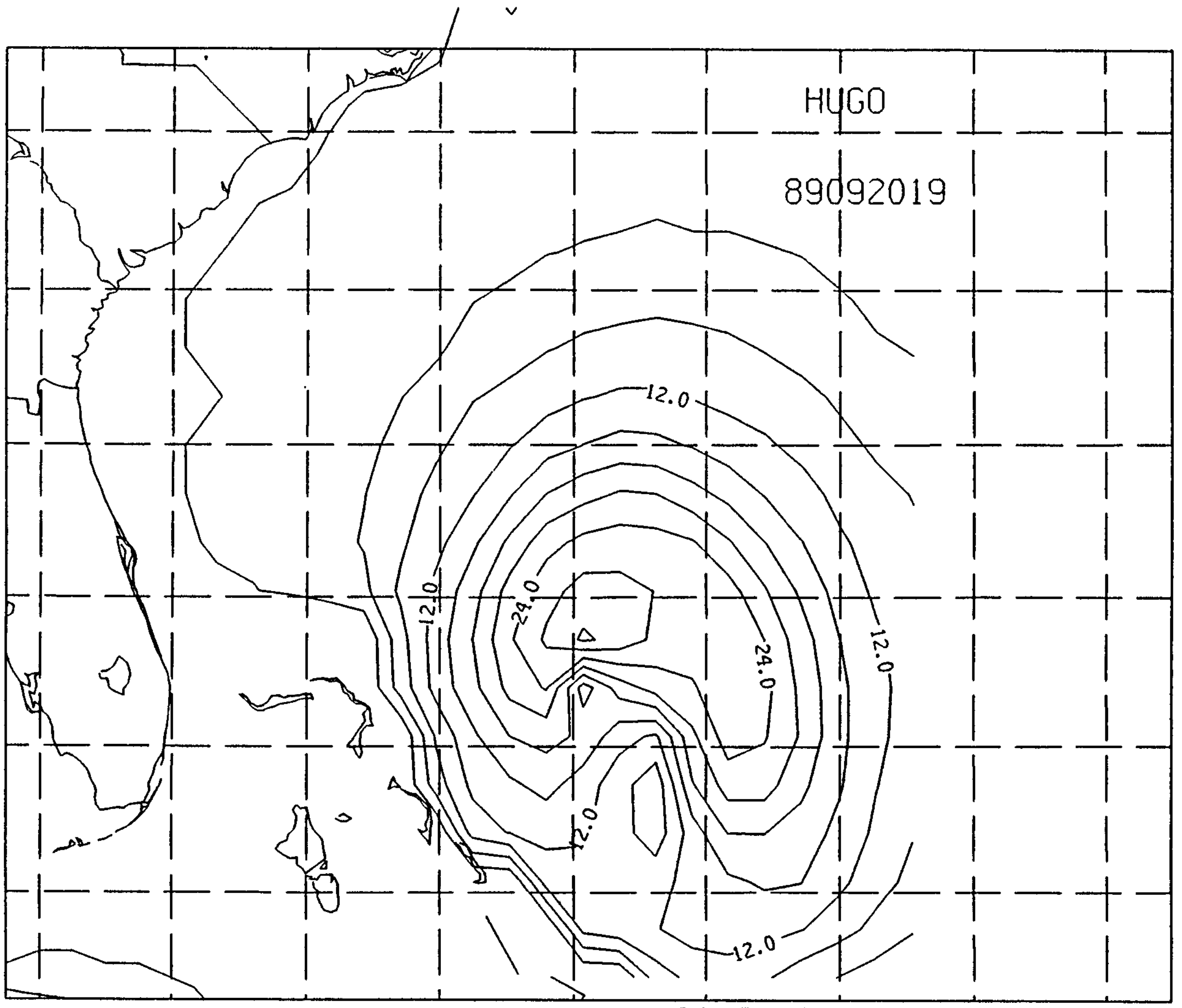

Fig. 20. Computed wave height distributions one day prior to Hugo landfall.

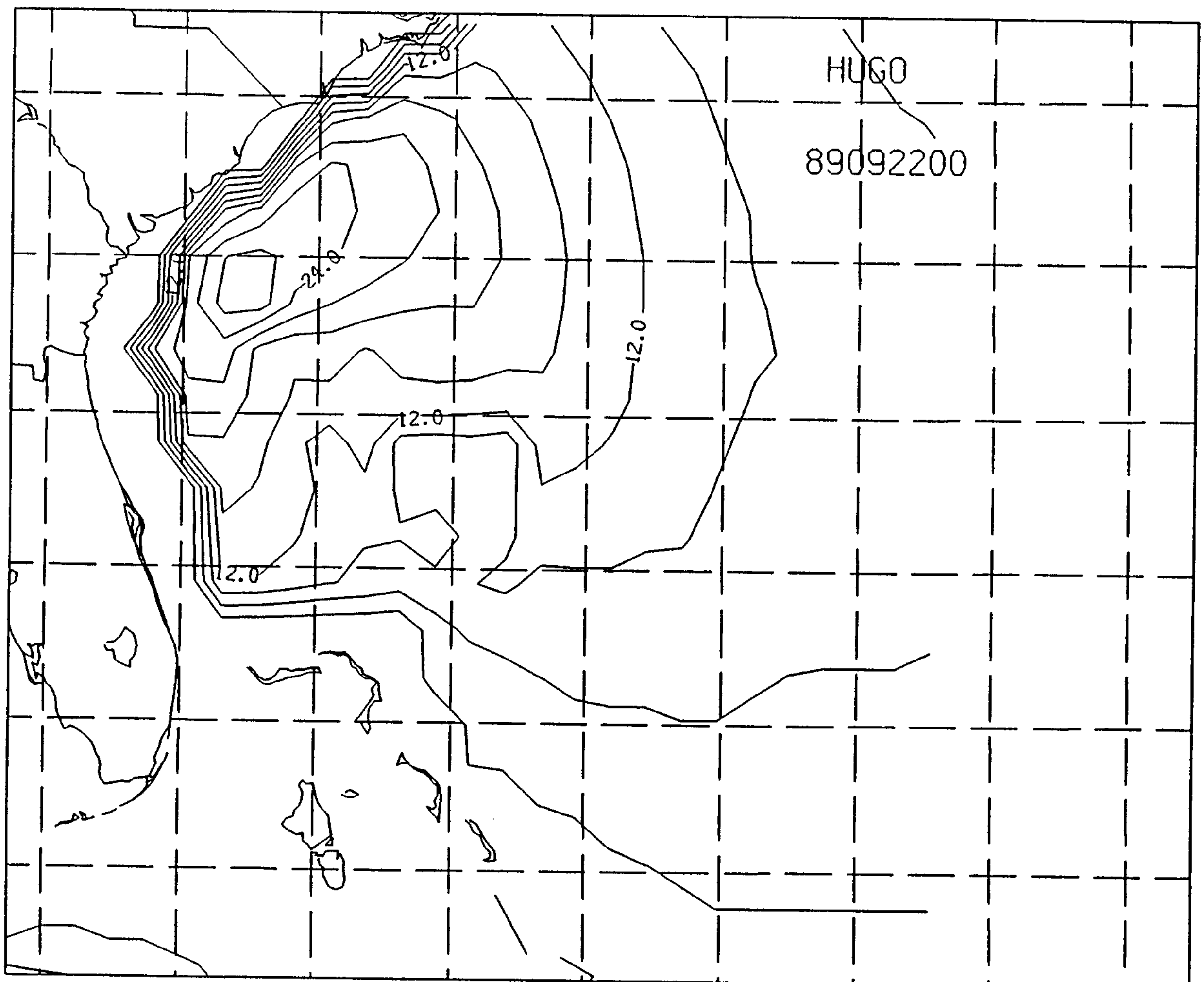

Fig. 21. Computed wave height distributions at Hugo landfall.

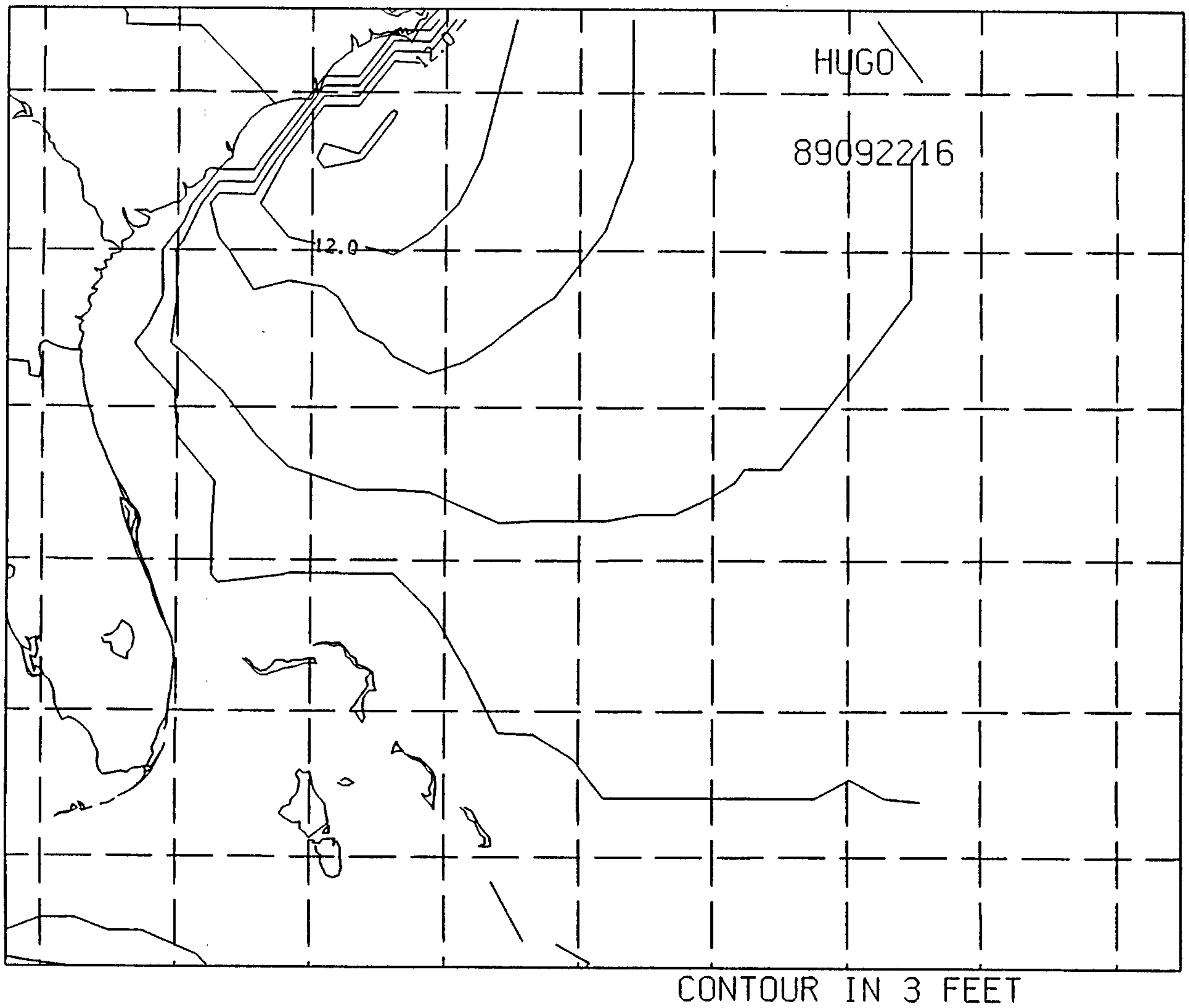

Fig. 22. Computed wave height distributions one day after Hugo landfall.

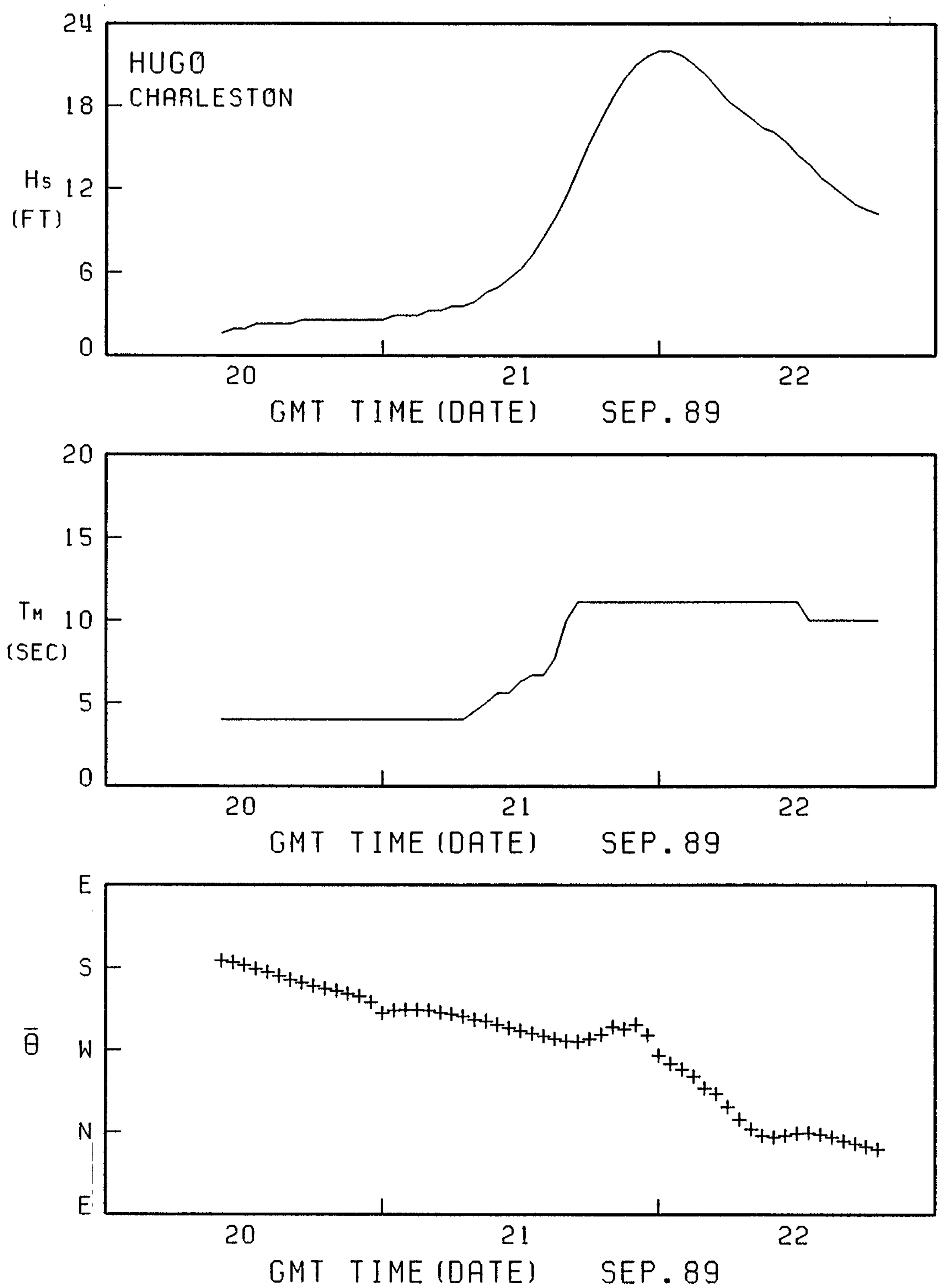

Fig. 23. Computed time history of wave height off Charleston, N.C. during Hugo.

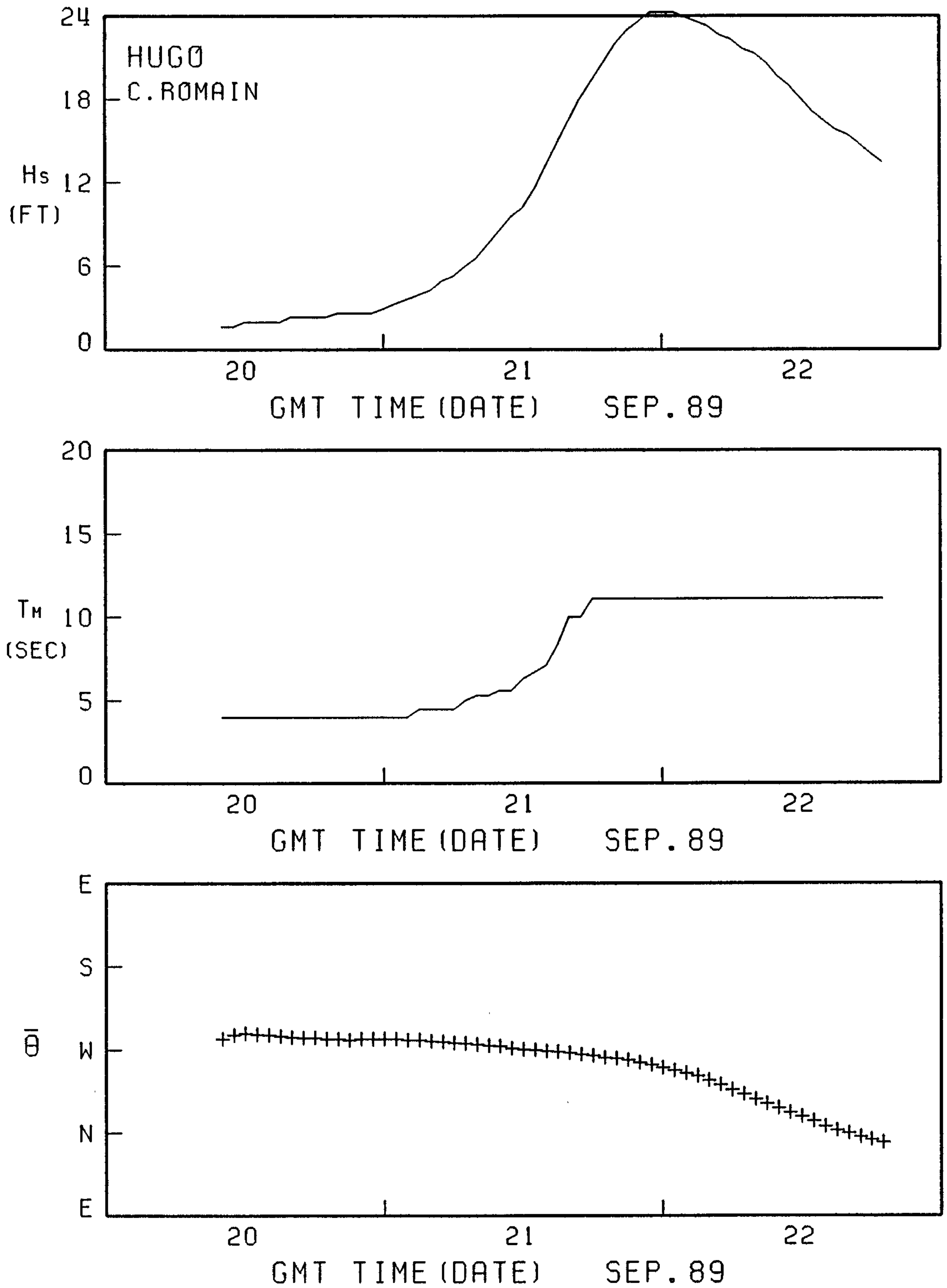

Fig. 24. Computed time history of wave height off Pawleys Island, N.C. during Hugo.

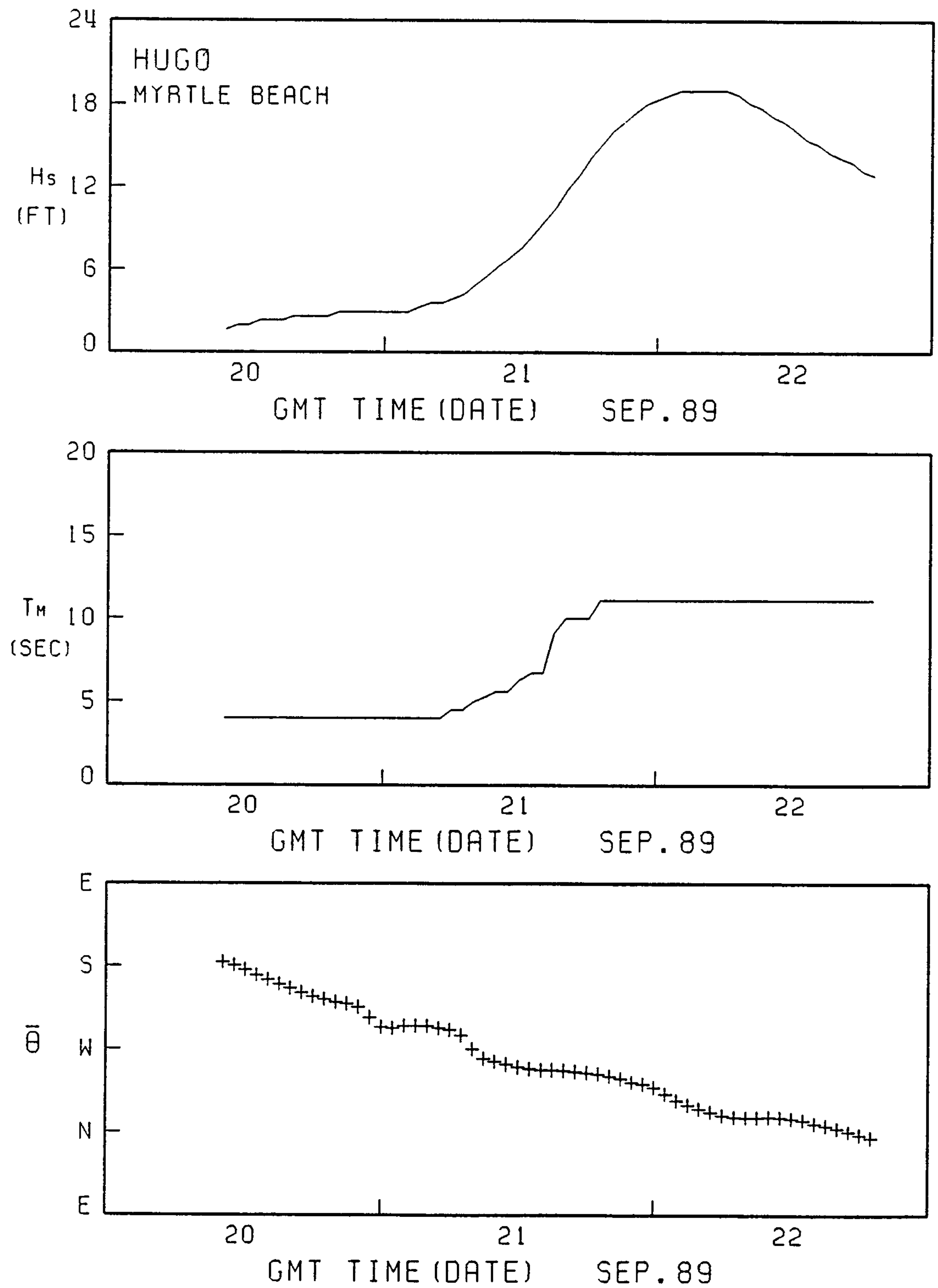

Fig. 25. Computed time history of wave height off Myrtle Beach, N.C. during Hugo.

static force as far as buildings and structures are concerned. The most dramatic effect of storm surge is to cause houses to separate from their foundations and float away. Figure 26 shows a slab-built structure floated away from its original site and deposited over 100 ft away across the street. The steady nature of this force is demonstrated here in that all the kitchen interior remained undisturbed. Most of the structures uprooted in this fashion were, of course, less fortunate as they crushed into other buildings, trees, etc. or simply disintegrated. The uplift force produced by storm surge is immense and most residential types of construction will be unable to withstand it. Force induced by a foot of storm surge, for instance, is approximately equivalent to that produced by 150 mph steady wind. Although the most dramatic effect is the uproot of entire structures the most prevailing storm surge damage is associated with flooding, as water once penetrates into a building the buoyancy effect is greatly reduced. As the hurricane passes, the storm surge retreats more rapidly than the rising stage owing to the aid of gravity. It is also a potent damage stage as the water now carries a large amount of debris towards the lee side of the structures.

Water waves constitute the most formidable destructive force compared with storm surges and winds. The destructive nature of waves is multi-dimensional. Some of the common modes of failure associated with waves are given here.

1. Erosion and Scouring

Figure 27 shows that erosion has exposed the pile foundation of this frame structure. Figure 28 shows the foundation material being completely scoured away around a bulky shallow footing. Shallow pier footings were exposed and eventually uprooted as shown in Fig. 29. Figure 30 shows the comparison of a residential structure before and after Hugo. The extent of the dune erosion was estimated to be about 60 ft in this case, exposing the structure in a vulnerable position. In addition to foundation scouring, erosion also led to the crumbling of porch slabs and garage floors and exposing utilities such as sewer lines, telephone lines, water mains and septic tanks.

2. Damage Modes Due to Direct Wave Loading

Wave loadings involve three forms: wave impact, velocity-related force commonly known as drag force and acceleration-related force also known as inertial force. Wave impact occurs when breaking wave slams on structures. The magnitude of this impact force is tremendous but hard to estimate. On the basis of field and laboratory measurements, the wave impact force on a flat surface could be as large as 3 to 6 times the incoming wave height. This is to say that a 3 ft wave would induce an impact loading up to 500 to 1,000 lb/ft^2. Clearly no residential-type structure can be designed to withstand this force. Un-reinforced or improperly reinforced piles or piers are also vulnerable to this type of loading. During Hugo, damages caused by wave impact were prevalent in the exposed area. Figure 31 shows piers broken by the wave impact. Figure 32 shows an entire masonry wall collapsed under wave loading. Seawalls of inadequate strength or backing also often fail under wave impact such as the case shown in Fig. 33.

Fig. 26. (a) Structure built on slab floated away from foundation and deposited 100 feet away across the street.

Fig. 26. (b) The arrangement inside the kitchen remained undisturbed in the house showing the static nature of the surge force.

Fig. 27. Pile foundation erosion due to waves.

Fig. 28. Bulky foundation promoted scouring around it.

Fig. 29. Shallow pier footings uprooted.

The wave drag and inertial forces are less violent but because of their oscillatory nature often contribute to structural failure by jolting loose the joints and connections. Structures of bulky volume and/or large projected surface towards incoming wave are particularly susceptible to damage and failure.

Finally, when waves overtop a structure or run up on a beach, the water motion becomes translatory like a bore. The momentum carried by this bore-like motion is one of the main forces breaking through walls and doors on the ground floor (Fig. 34) and causing appurtenant structures such as beach access ramps to crush into the main structure (see Fig. 30).

3. Damage by Water-Borne Objects

Water-borne objects vary in size and shape. The damages caused by these floating objects were pervasive during the Hugo experience. Objects as large as an entire house or as small as rocks and stones were being thrown around by surges and waves. Revetment stone was an often found object breaking doors, windows and walls (Fig. 35) as were furniture, tree branches and other debris. A back row house could be crushed by a floating house or a water tank. Therefore, damages caused by floating objects are hard to define and even more difficult to prevent.

Fig. 30. (a) Photo taken prior to Hugo.

Fig. 30. (b) After Hugo the protective dune was gone and the access ramp was washed into the house due water force.

Fig. 31. Pier foundation broke by wave impact.

Fig. 32. The load-bearing masonry wall was destroyed by wave force.

Fig. 33. Seawall failure due to wave impact loading.

Fig. 34. First floor breakaway walls completely gone due to bore-like water motion (the house is on the second row in the water runup zone).

Fig. 35. Stones from revetment thrown by waves into the house supposed to be protected by it.

Wind Force and Associated Damage Modes

In Andrew, the damage was almost exclusively caused by high wind. Coastal flooding was limited to a few spots in Key Biscayne and a few canal-front communities along the coast off Cutler Ridge. Damage due to rainfall, though extensive, was the consequence rather than the cause of structural failures.

Common meteorological terms used to describe hurricane wind strength are "sustained wind" and "wind gust". The sustained wind is defined as the average wind speed over a one-minute period; the gust, on the other hand is the highest wind speed over three-second period. Wind is a fluctuating air motion, commonly the shorter the averaging duration the higher the wind speed. Both wind speeds are supposedly reported at an elevation 10 M (33 ft) off the ground, known as the standard instrument height (the standard height where the wind anemometer is installed). In engineering community a term called "fastest-mile wind" is often used. The fastest-mile wind is neither the 1-minute sustained wind nor the gust wind. The fastest-mile wind has a floating time-averaging scale. It is determined by examining the wind record and selecting the segment with the fastest speed such that the average wind speed over this segment will travel a one-mile distance. Thus, a 60 mph fastest-mile wind has an averaging time of 1 minute. A 120 mph fastest-mile wind, on the other hand, has an averaging time of only 1/2 minute. In practice, engineers very liberally use the sustained wind as the fastest-mile wind. Also, since the wind speeds are reported at an elevation 10 M above the ground, the wind speeds at elevation lower than 10 M should be smaller owing to the resistance offered by the surroundings including trees, neighborhood buildings, etc. A simple power law can be used to prescribe the vertical distribution of wind speed:

$$U_z = U_{10} \left\{ \frac{Z}{10} \right\}^m$$

Where U_{10} is the wind speed at Z=10 m. The exponent m is a function of wind speed and surface characteristics. For overwater high wind speeds, m is usually taken as equal to 0.14. Thus, at 5 m elevation the wind speed reduction is about 10%. For ground covered with trees and buildings a larger value of m should be used. For example, if m assumes a value of 0.3 the wind speed reduction at 5 m elevation is about 20%. Gust, because of its short duration, is less affected by the ground resistance. The m value for over water gust is usually assumed to be in the order of 0.08.

The nature of wind- and water-loading on buildings and structures is somewhat different although both are caused by fluid motion. Since air density is much smaller than that of water, the inertial force induced by air motion can generally be neglected. Also, in water loading, a fluctuating air-water interface usually intersects the structure which induces variable buoyancy force as well as rendering the structure susceptible to impact forces. On the other hand, a structure is always submerged in air, therefore, buoyancy force is constant and negligible and impact loading is completely absent. However, forces induced by pressure difference are now far more important than that in the case of water loading. This pressure difference is closely related to the velocity field surrounding the structure and could be positive or negative with respect to the interior pressure of the building. Furthermore, hurricane winds are gusty and its effects are manifested in rapid spacial and temporal changes of wind velocity and direction. Consequently, the wind loading on a structure is also unsteady and changes its magnitude and direction rapidly.

In this section, the observed structural failure modes due to wind loadings are described. Since Andrew has caused such extensive wind damage, in depth investigations on this subject are being conducted by numerous investigators and committees. The intent here is not to provide a comprehensive damage survey. Rather, the emphasis is to identify the various failure modes.

The integrity of a building depends mainly on the strength of structural elements and the connections between them. The structural elements can be loosely classified as building material elements and structural components. Cinder blocks, roof shingles, two by fours, wall panels, etc. belong to the former category whereas roof frames, loadbearing and non-loadbearing walls, foundations, doors, windows, etc. are considered as structural components. Also, the connection can be viewed from its method and its function. Nails, screws, mortar joints, staples, tongue-and-grooves, etc. are methods of joints whereas providing resistance against shear, tension, compression, bending, torsion, etc. are the functions of joints. Though not always possible but clearly beneficial, one can strive to identify and isolate the failure modes in the terms given above so proper corrections can be made in the future.

1. Roof Damage

For residential-type structures, roof damage has been singled out as the most prevalent wind-related damage mode by practically every post-hurricane survey report including Hugo and Andrew. However, only after Andrew has there been a strong demand from the engineering community itself to seriously review the current practice in roof construction. Prior to Andrew, wind-related roof damage was usually scattered over a large area and was not considered as the major cause leading to building failure.

In Hugo, the actual winds in most of the affected coastal communities were less than the code specified design speed. The majority of the damage was in the form of partial loss of roof coverings. Overall roof failures with simultaneous collapse of walls were found mainly in exposed locations and most of them were scattered. Clustered roof failures of 7 to 10 houses in a row were clearly led by the collapse of supporting structure due to water loadings. In Andrew, the extent and nature of roof damage were very different. Earlier survey reports (Florida Department of Community Affairs, 1992) indicated that 90% of residential structures from North Kendall Drive to Florida City sustained roof damage of varying degrees. Overall roof failures over a cluster of structures or even an entire housing section were common in the high wind intensity zone from Cutler Ridge to Florida City (sustained wind speed above 130 mph). Therefore, massive roof failure appeared to occur in zones where the design wind was exceeded (the design wind load in this region is 120 mph). Some of the frequently observed failure details are given as follows:

A. Loss of Roof Coverings:

Roof coverings are subject to shear force on the windward side and to suction force on the leeward side. In Hugo, most of the roof covering loss was composition shingles. Also, loss on windward side was more prevalent. The failure of newer roof shingles was mainly due to inferior connection (staples or nails). Turned shingles were mainly found in older structures. In Andrew, the loss of composition shingles occurred on practically all the roofs within the high wind zone of over 130 mph. In some regions, both windward side and leeward side sustained extensive damage. In certain regions, damage was more prevalent in the windward side; and in yet other regions, damage was mainly on the leeward side. Therefore, it was difficult to sort out whether the main cause of failure was due to shear or tension (suction). One could only surmise from the general impression that shear failure initiated earlier than suction failure. Losses at gable ends were clearly heavier than the center section. However, many of these gable-end failures were also associated with loss of roof sheathings. Stapled shingles fared the worst. Torn shingles were also numerous. Roofs with a high pitch appeared to fare slightly better. There was no clear evidence that a more streamlined roof configuration would aid in the retention of roof material; some isolated cases seemed to indicate the contrary.

In addition to composition shingles, loss of tile shingles was also heavy in Andrew but not in Hugo. In this case, high-pitch roofs have clearly performed better. One of the examples was the slight or no damage condition found in Howard Johnson hotels that feature high pitch tile roofs. Failure of tile shingles was mainly caused by inadequate mortar bound and improper installation of the mortar pads or underlayings. Metal roofs such as shown in Fig. 36 appeared to be a viable alternative for low cost roofs in high wind regions as many of them, both in Hugo and in Andrew, remained intact.

Fig. 36. Metal roofs usually require simpler connection to sheathing appear to perform better in hurricane winds.

In summary, loss of roof coverings in Hugo was mainly due to inadequate connection; the damage was rather scattered and occurred mainly on the windward side. In Andrew, in addition to inadequate connection, material failure was also evident; damage was much severe and widespread and occurred on both windward and leeward sides.

B. Loss of Roof Sheathing:

In Hugo, loss of roof sheathing directly attributable to wind was less than in recent hurricanes. In Andrew, it was far more. Inadequate connections were the main cause due either to missed nailing to roof truss, inadequate nail spacing and/or nail size. As stated earlier, gable-end losses were heavier than center section. It appeared that eaves or overhangs often contributed to roof loss.

C. Failure of Roof Truss System:

Roof framing systems were mainly composed of prefabricated wood truss frames fastened to the bearing walls by nails and metal strips. Failure of individual frame due to inadequate material strength was rare. The two major modes of failures were the lateral and the vertical collapsing of the ensemble. Of these two, lateral collapsing was more frequent and was found in both Hugo and Andrew. Vertical collapsing was mainly found in Andrew. The roof ensemble could also fail due to torsion; however, this mode is hard to clearly identify.

Lateral collapsing often initiates at the gable end of the roof. In current roof construction practice, the lateral bracing between individual frame relies mainly on the sheathing. Additional lateral bracings are usually for the purpose of holding the frames together during construction. This practice proved to be one of the main causes of roof framing failures. Figure 37 shows one of numerous gable-end roof failures initiated by the loss of sheathing which then led to the lateral collapse of roof frames. Since usually the exterior of the gable end is a vertical extension on a non-loadbearing wall that offers little lateral strength, the collapse of roof frame also lead to failure of this wall extension. As can be seen in the same figure the vertical extension was disconnected from the wall and collapsed.

Vertical collapsing is usually associated with the failure of the bearing walls. Unlike the later collapsing, here the roof system failure is the effect not the cause. This failure usually was initiated at the center span of the structure. Figure 38 shows the vertical roof collapse as a consequence of the failure of the masonry wall that supports the roof. Here, the concrete roof beam that is seen separated from wall still partially holds the roof system together. Figure 39 shows the bearing wall failure of a frame structure that lead to the vertical collapse of the roof.

2. Wall Damages

The most common wall damage was caused by broken doors and windows. The failure of doors and windows not only weakens the structural integrity but also causes pressure built-up in the interior due to wind penetration. In frame structures, this often results in large structural member deformation leading to joint separation and wall collapsing. Most built-in hurricane shutters, even those with inadequate structural strength, were found to be helpful. Figure 40 shows a case of a marginal hurricane shutter which did not prevent the window from being shattered but helped to hold the structural members together and reduced wind penetration. Temporary window boards were ineffective in strong winds as they tended to separate from the base wall under negative pressure. Large windows and sliding doors are also difficult to cover with an integral piece of board of adequate strength.

Masonry wall failures were mainly due to inadequate shear reinforcement (vertical reinforcement) in the wall and inadequate anchoring to the foundation. Figure 41 shows the failed wall revealing no re-bar and no mortar fill. The shear resistance is mainly provided by the friction between blocks due to the weight of the roof system and the roof beam. Once the

Fig. 37. Gable end failures were most common due to weak lateral bracing, causing lateral collapsing of roof frame.

Fig. 38. Vertical roof collapsing due masonry wall failure.

Fig. 39. Framed wall failures led to vertical roof collapsing as well.

Fig. 40. Even marginal hurricane shutter helps.

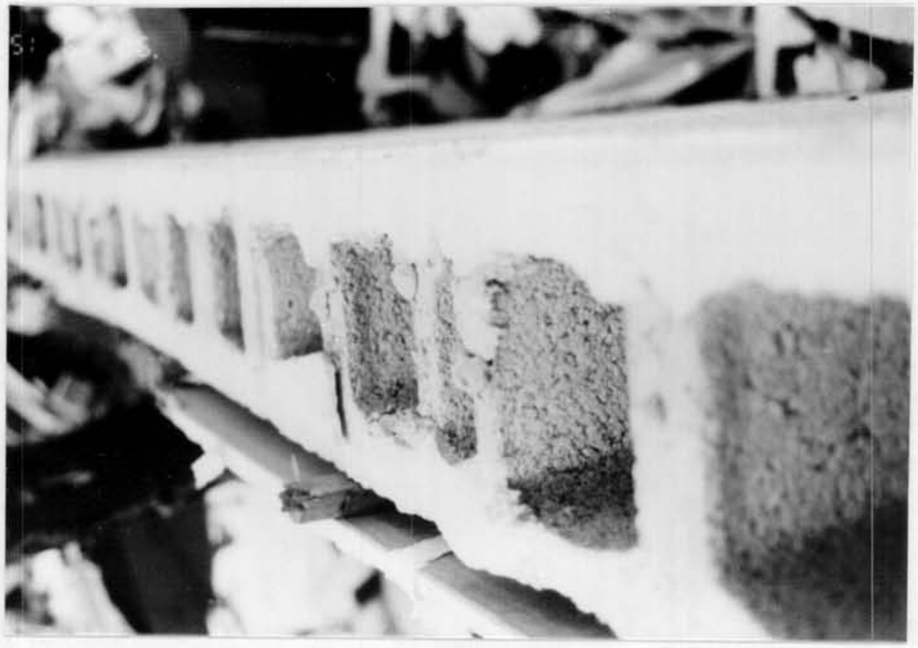

Fig. 41. Un-reinforced masonry wall failed due to insufficient shear resistance to wind loading.

lateral wind load overcomes the friction resistance the wall begins to disintegrate. The most vulnerable location appeared to be just below the roof beam.

Failure of framed structure walls was mainly due to inadequate connections. Wall frames are usually nailed to the base and to connecting wall frames. Metal strips should be used to provide added shear strength but were not always found in the damaged structures. The common mode of failure was the separation of the entire wall panel from the base as shown in Fig. 42. Here, it is also revealed that the metal strips, all on one side, did not provide any added resistance to negative pressure, nor to moment. The gable-end non-loadbearing walls on the second floor of two-story frame structures were particularly prone to this mode of failure. This probably was the leading factor causing major structural damage. Failures that can be attributed directly to inadequate building material were not common but did exist. Figure 43 shows practically all the exterior wall panels in this multi-story building failed. The wall frames were metal 2x4's, covered with a layer of Styrofoam and a layer of masonry cladding. This structure was an exception to multi-story buildings which, in general, fared well in terms of structural damage. It is an example of the worst. In residential structures, failures due to inadequate material were more prevalent. Figure 44 shows the material failure of exterior wall panel made of manufactured board.

Fig. 42. The most common failure of frame-walls was the collapsing of the entire section revealing the grossly inadequate connection method in the current construction practice.

Fig. 43. Inadequate material strength led to this devastating wall failures of a multi-storied building.

Fig. 44. Damage to exterior wall due to inadequate material strength of the manufactured board.

3. Manufactured Homes

Manufactured homes, commonly known as mobile homes, are generally perceived as prone to catastrophic failures under hurricane-type wind loading. After Andrew, there are demands that mobile homes be banned.

To examine manufactured home damage, one probably should separate the "manufactured" and "mobile" aspects of the unit as the former refers to the structure being factory "manufactured" whereas the latter refers to the attachment of modular unit to the foundation being "mobile". In an attempt to sort out the failure modes, the author and his assistants surveyed a cluster of 68 units in a heavily damaged mobile home area named Gold Coaster Mobile Home Park located in SW 348th Street in Florida City.

Most of the mobile home units in this cluster are along the east and west sides of 187 ct. which is aligned in a N-S orientation such as shown in the Fig. 45. Therefore, the broadsides of these units are mainly N-S oriented. On the basis of visual survey, the west end of the units, in general, sustained heavier damage than the east end. For those units separated from the foundation, they usually fell broadside towards north. The trees in the adjacent field mostly fell towards east. Therefore, judging from the failure orientations, strong wind was from west or south-west, or the park is located close to, but on the left hand side of the wind track.

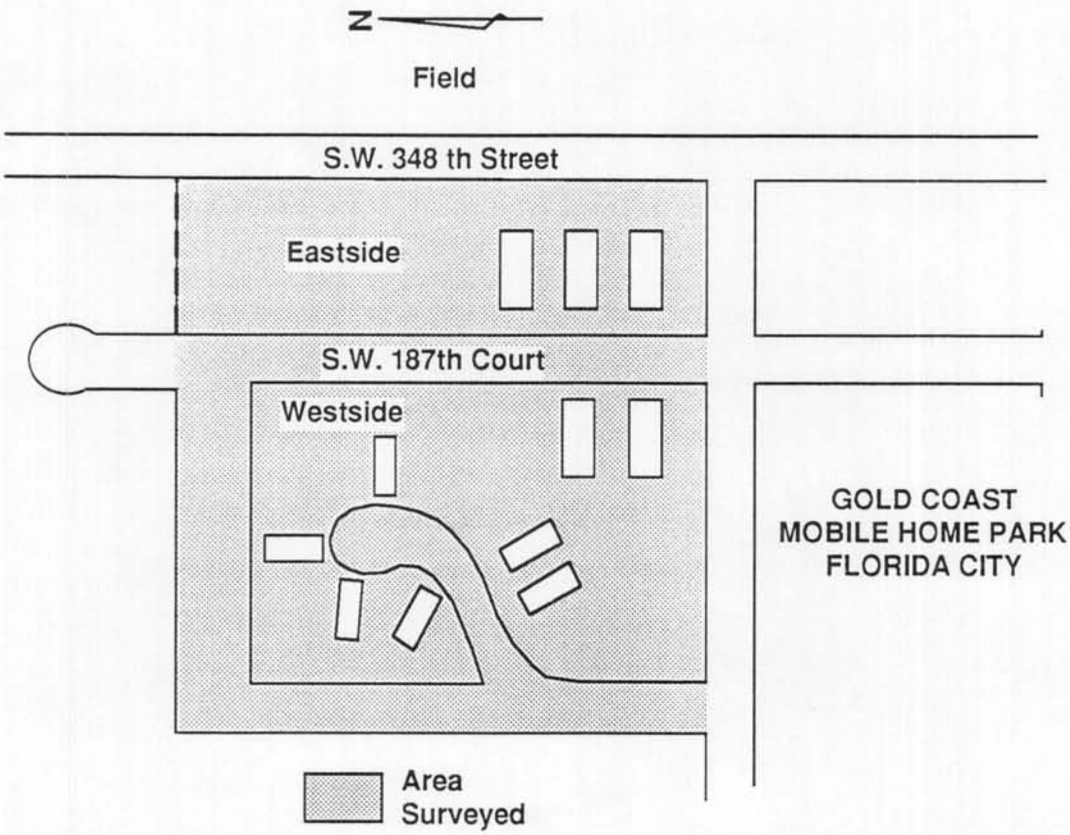

Fig. 45. Sketch of the mobile home park surveyed after Andrew.

The survey was conducted by visual inspection and inspected units were placed into 6 separate categories as follows:

1. Superstructure destroyed with foundation shift.
2. Superstructure destroyed with no foundation shift.
3. Superstructure damaged with foundation shift.
4. Superstructure damaged with no foundation shift.
5. Superstructure intact with foundation shift.
6. Superstructure intact with no foundation shift.

A destroyed unit is defined as one deemed structurally not repairable or more than 2/3 of the frame damaged. An intact unit is defined as sustained light or no damage and is readily habitable. A damaged unit is in between the two. Of the 68 units inspected there was no unit in category 5 or 6. All units were either damaged or destroyed. Figure 46 shows a destroyed unit (foreground) against a damaged unit (background). The base of these mobile homes typically is a steel frame composed of two light I-beams linked by cross members (Fig. 47). The base is then rested on low pier footings. The quality of the pier footings varies greatly; some of them are simply stacked cinder blocks as shown in Fig. 46 whereas others are more substantial,

Fig. 46. Destroyed mobil home unit with a damaged unit in the background.

Fig. 47. Mobile home foundation frame and pier footings.

bounded and filled by mortar. Most of the mobile home units have hurricane anchors with metal bands wrapped around the structure and/or the steel base. A foundation shift means either visible relative displacement between the base and the pier footing or the displacement of the footing itself.

The survey results are given in Table 2.

Table 2: Tabulation of Mobile Home Damage

	Units			Percent
Destroyed units	52			76%
with foundation shift		30	44%	
with no foundation shift		22	32%	
Damage units	16			24%
with foundation shift		6	9%	
with no foundation shift		10	15%	
Total	68			100%

From this survey results and our visual observation, we are unable to attribute foundation shift (here can be viewed as the failure mode of mobile foundations) as the main factor leading to structural failure. Our impression seemed to be the contrary.

There are a number of identifiable causes that contribute to the devastation of the manufactured homes. Clearly, the main cause is simply that these structures are not designed to withstand the hurricane wind intensity. The structural frames, roof frames, sidings and roofings (Fig. 48) are all lighter than conventional residential structures. Broken tie-down metal strips, usually in the vicinity of the anchors, was another commonly observed failure mode. Anchor failure, on the other hand, was not observed. The proximity of mobile homes contributed greatly to damages. Many of them were simply destroyed or crushed by the failed neighboring structures.

In summary, in contrast to conventional structures, the failure of manufactured homes is mainly due to inadequate material strength rather than weak connections. In fact, manufactured homes often exhibit superior connections than many of the conventional residential constructions in the region devastated by Andrew. This is particularly evident in the roof system (the light roof framing and the metal roof covering often remained intact). Similar situation was observed in modular homes which actually fared better than on-site erected housings. Failure related to foundation is largely due to under-designed tie-down strips, inadequate footings.

Fig. 48. Typical construction of mobile home revealing the nature of light wall frames, roof structure and material.

The Reverse Scenario

Andrew and Hugo were very different hurricanes. A natural question to ask is which one was more devastating? Also, since they inflicted damages of a very different nature, are we reacting appropriately in our post-disaster remedial measures so as to be better prepared for the next event? After Hugo, the reaction in the South Carolina's coastal communities was to relocate sand to protect houses and to raise the elevation of the structures. Other repairs such as roofings, wall framings, sign erections went on with business as usual. Figure 49, for instance, shows a house being raised with new pilings in an apparent attempt to be readying for the next hurricane's high storm surge. It is also evident that the superstructure itself is in a questionable state to survive a hurricane with high wind intensity. After Andrew the affected towns and counties were demanding to ban mobile homes, to raise design wind speed and to revise roof designs. The coastal communities, on the other hand, had a sense of relief and certain degree of euphoria; some even went on to claim that the beaches in this region had survived the test of the worst hurricane. Therefore, it would be useful to examine the scenario if these two hurricanes were to switch their roles.

In Fig. 50, the wind field and storm surge distributions of Andrew are superimposed on the South Carolina coast at the same landfall location as Hugo. In this case, the 140-mph influence zone would mainly be over a sparsely populated forest region. The associated damage would, perhaps, not be any greater than Hugo as the pine forest would be demolished anyhow

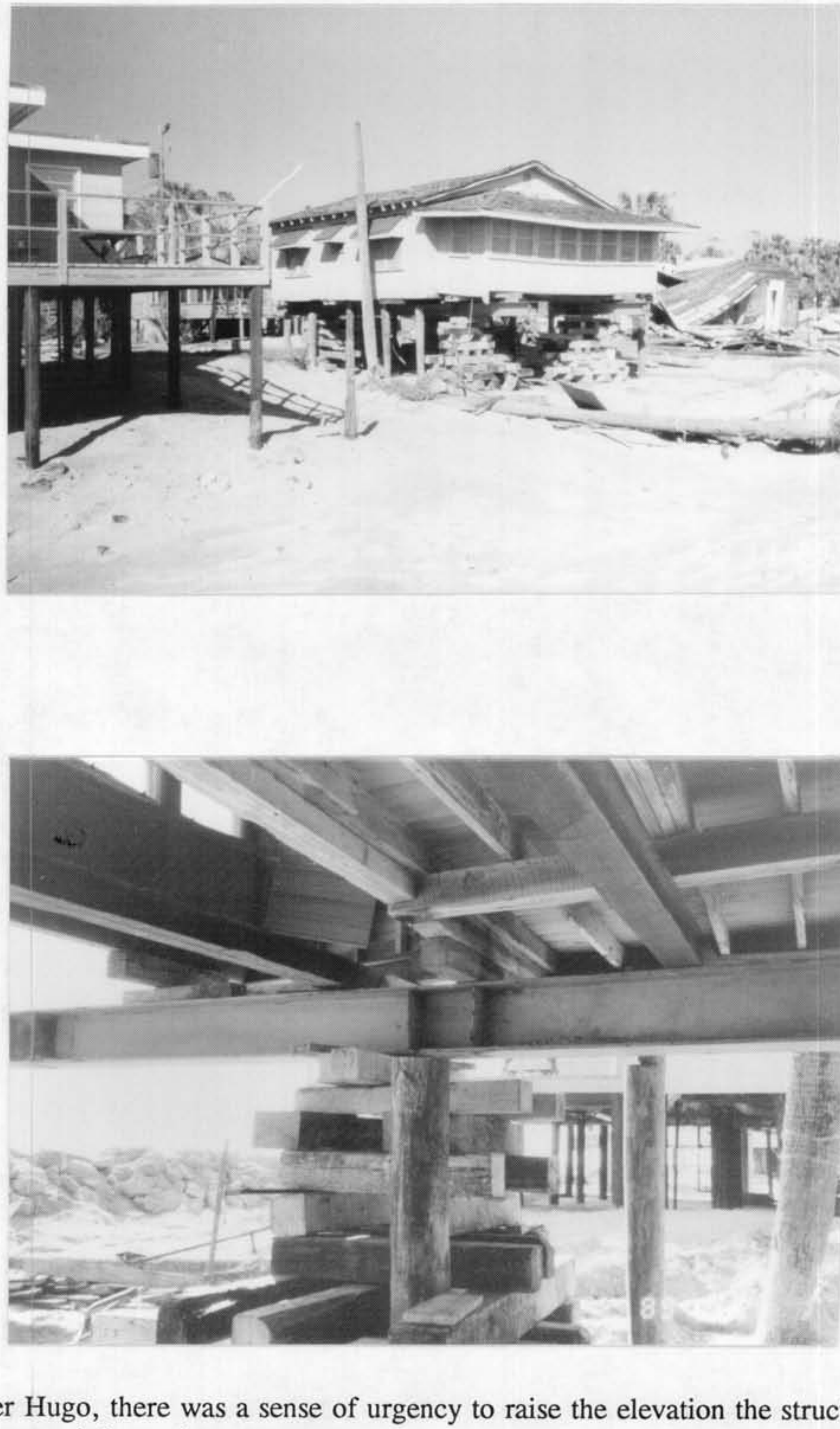

Fig. 49. After Hugo, there was a sense of urgency to raise the elevation the structures without parallel effort to reinforce the structure.

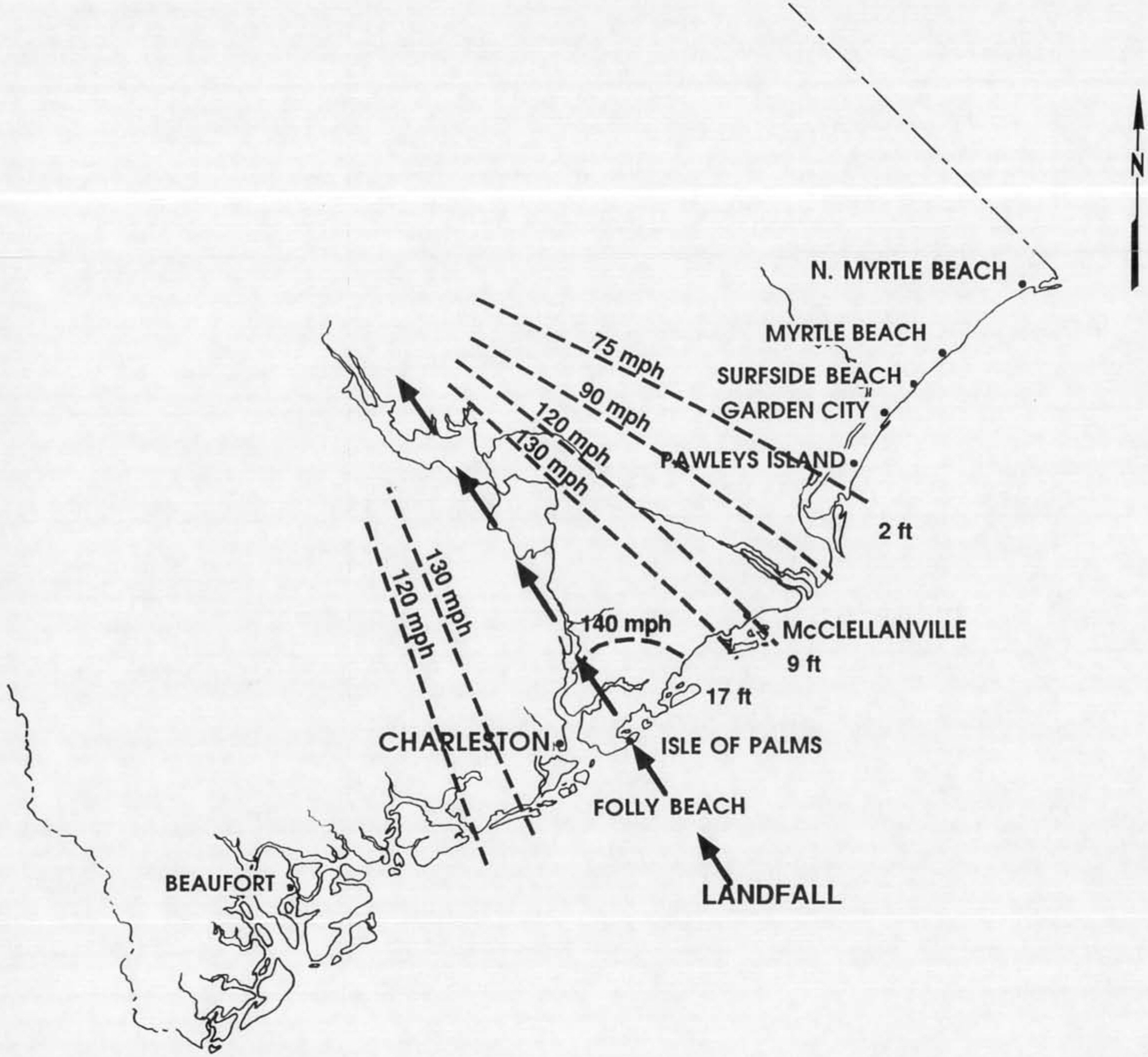

Fig. 50. Wind field and highwater elevations corresponding to Andrew being superimposed at the landfall location of Hugo.

when wind speed exceeds 100 mph. The populated areas including Charleston, Isle of Palms, Sullivans Island and Folly Beach would now be within the 130 mph envelope instead of the 90 mph zone as experienced in Hugo; wind damage to these exposed barrier island locations would be substantially increased, perhaps, by as much as 3 to 4 folds with devastation similar to the high wind intensity zones in Andrew such as Kendall or even Cutler Ridge. Water-related structural damage would, on the other hand, be drastically reduced because the high storm surge zone, on the north of the track, would be over a swamp area with very low population density. Damage to utilities and other infra-structures would not be nearly as wide spread as Hugo. The damage to the Charleston airport (which only sustained light damage in Hugo) would be extensive so as to the Charleston Harbor.

Now, what would happen if Hugo were to hit south Florida instead of Andrew? Since Hugo was a persistent hurricane which took over 8 days after reaching hurricane strength to hit the shore, the associated waves were much more powerful than those of Andrew. Therefore, if Hugo were to follow Andrew's track it would also generate more powerful waves than Andrew, although not as powerful as that experienced in the South Carolina coast owing to the shielding of the Bahamas Banks. To assess the potential of wave damage the wave forecast model discussed earlier is used to simulate the wave conditions for this hypothetical hurricane; Fig. 51 shows the wave height contours of this simulated hurricane during landfall. The simulated time history of the wave condition of this Hugo-type hurricane is superimposed upon that of Andrew as given in Fig. 52 for Miami Beach location. Figure 53 shows similar comparison but for West Palm Beach region which is at the fringe of hurricane influence. As can be seen the waves are much more powerful for the Hugo-type hurricane, and the duration of high waves is also much longer. As stated earlier, in Miami, the maximum significant wave height associated with Andrew's wind field is about 8 ft with wave period less than 7 sec. The duration of high waves over 6 ft only lasts about 18 hrs. For Hugo-type hurricane, the waves would be higher and longer; thus, would contain more energy. The maximum significant wave height would have reached 13 ft with 10 sec period. High waves exceeding 6 ft would pound the beach 48 hrs instead of 18 hrs as during Andrew. Therefore, considerable beach erosion would be expected. The situation would be similar in West Palm Beach only the waves would be higher than Miami because it is located outside the shadow of the Bahamas Banks.

To assess coastal flooding, Figure 12 (reproduced here) shows that the coastal region from Cutler Ridge to as far north as Boca Raton would practically be inundated with surge level exceeding 14 ft. Over 10 ft of water would be experienced as far north as West Palm Beach. The horizontal extent of this highwater level coupled with the high waves all the way beyond West Palm Beach would certainly translate into extensive water related damage along one of the most densely populated coastal belts in the United States.

Now, what would be the expected wind damage? In Fig. 54 we overlay the Hugo's wind field over south Florida with the same track as Andrew. Now the 140 mph zone is roughly replaced by the slightly smaller 130 mph zone. The City of Miami would still be located within the 90 mph wind envelope and in addition this wind zone would now extend to Ft. Lauderdale. Hurricane wind strength (75 mph) would be felt beyond Boca Raton. Therefore, although the

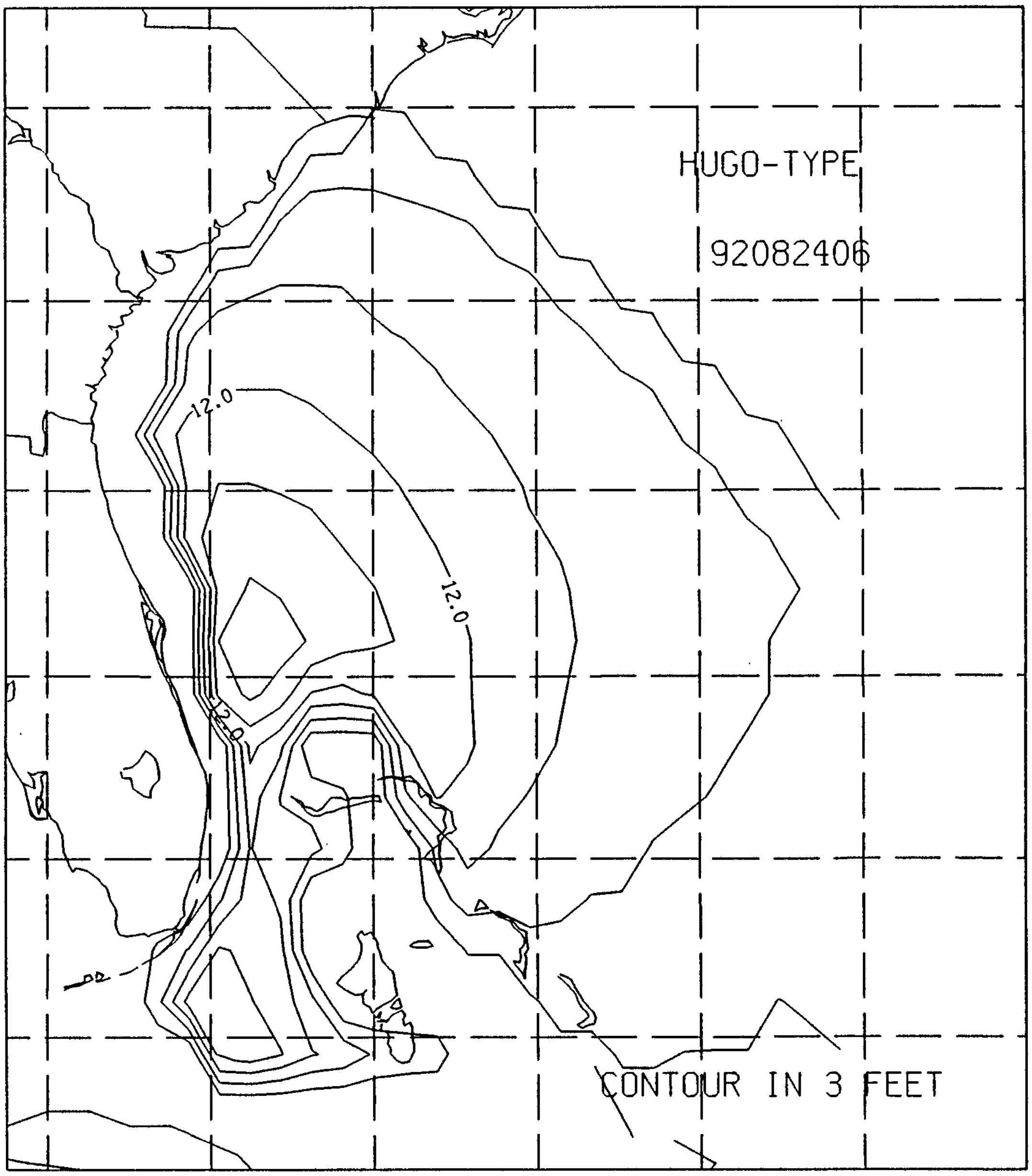

Fig. 51. Computed wave height distributions due to Hugo-type wind field following Andrew's track.

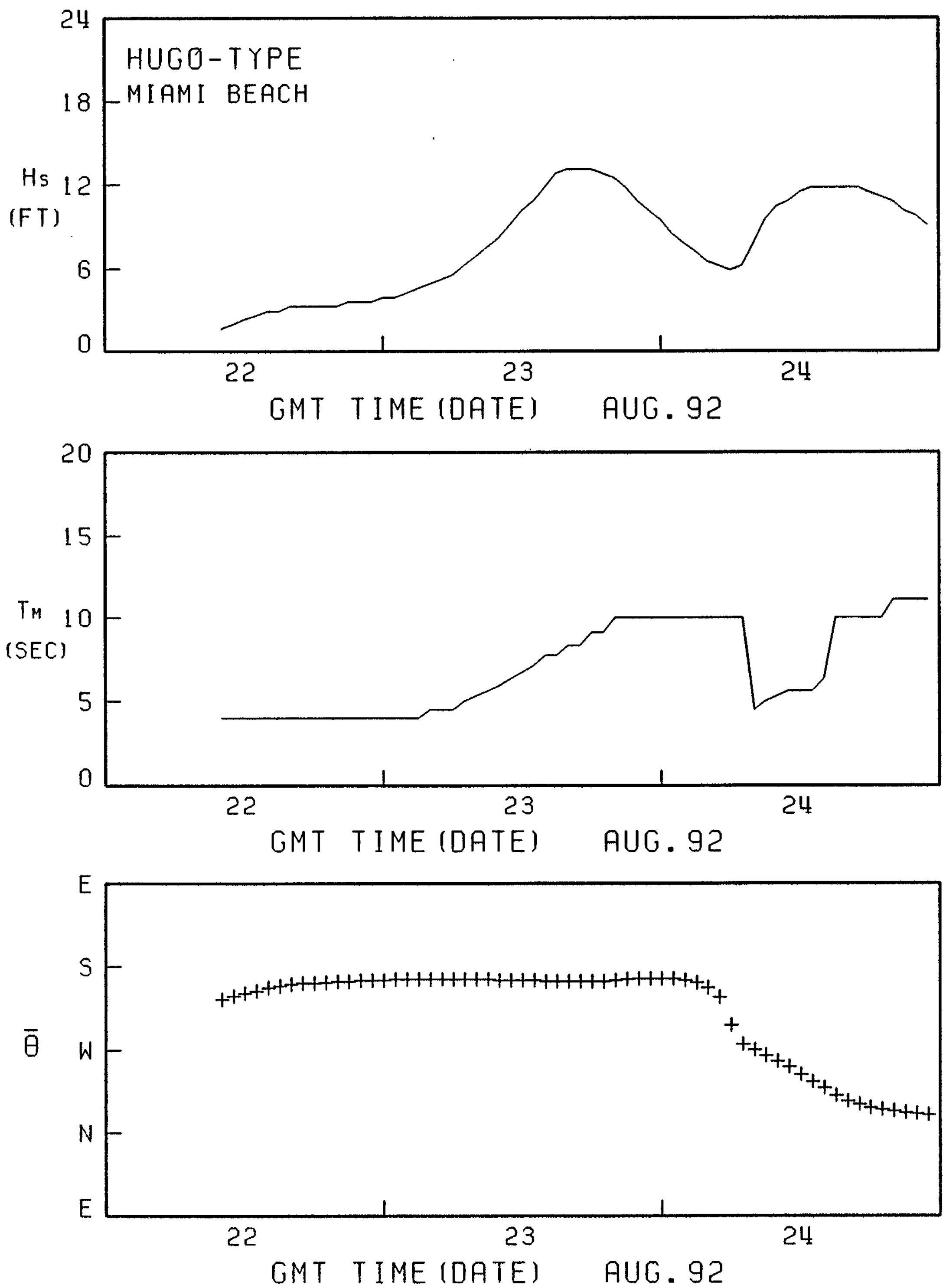

Fig. 52. Computed time history of wave height at Miami Beach due to Hugo-type hurricane wind.

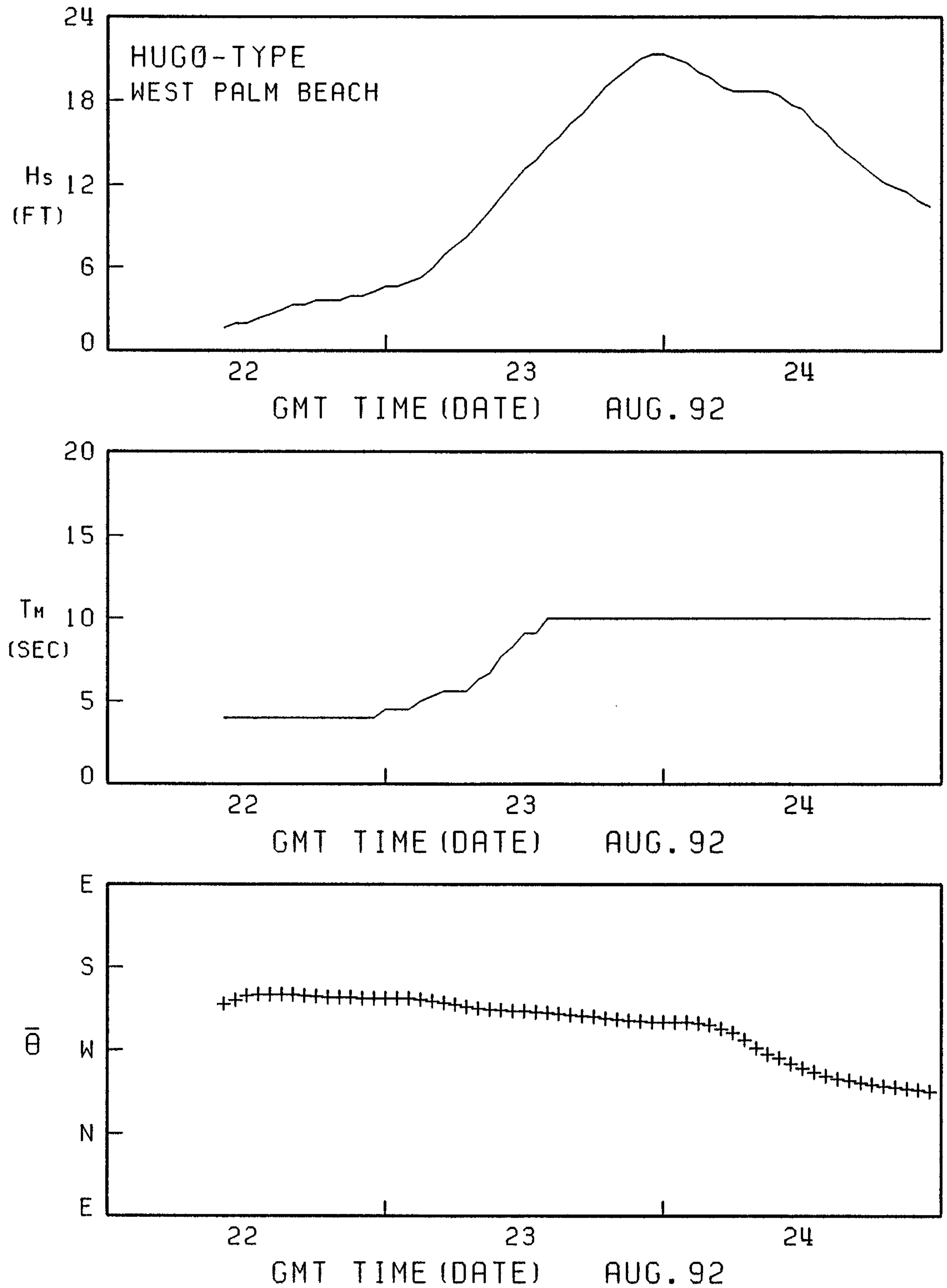

Fig. 53. Computed time history of wave height at West Palm Beach due to Hugo-type hurricane wind.

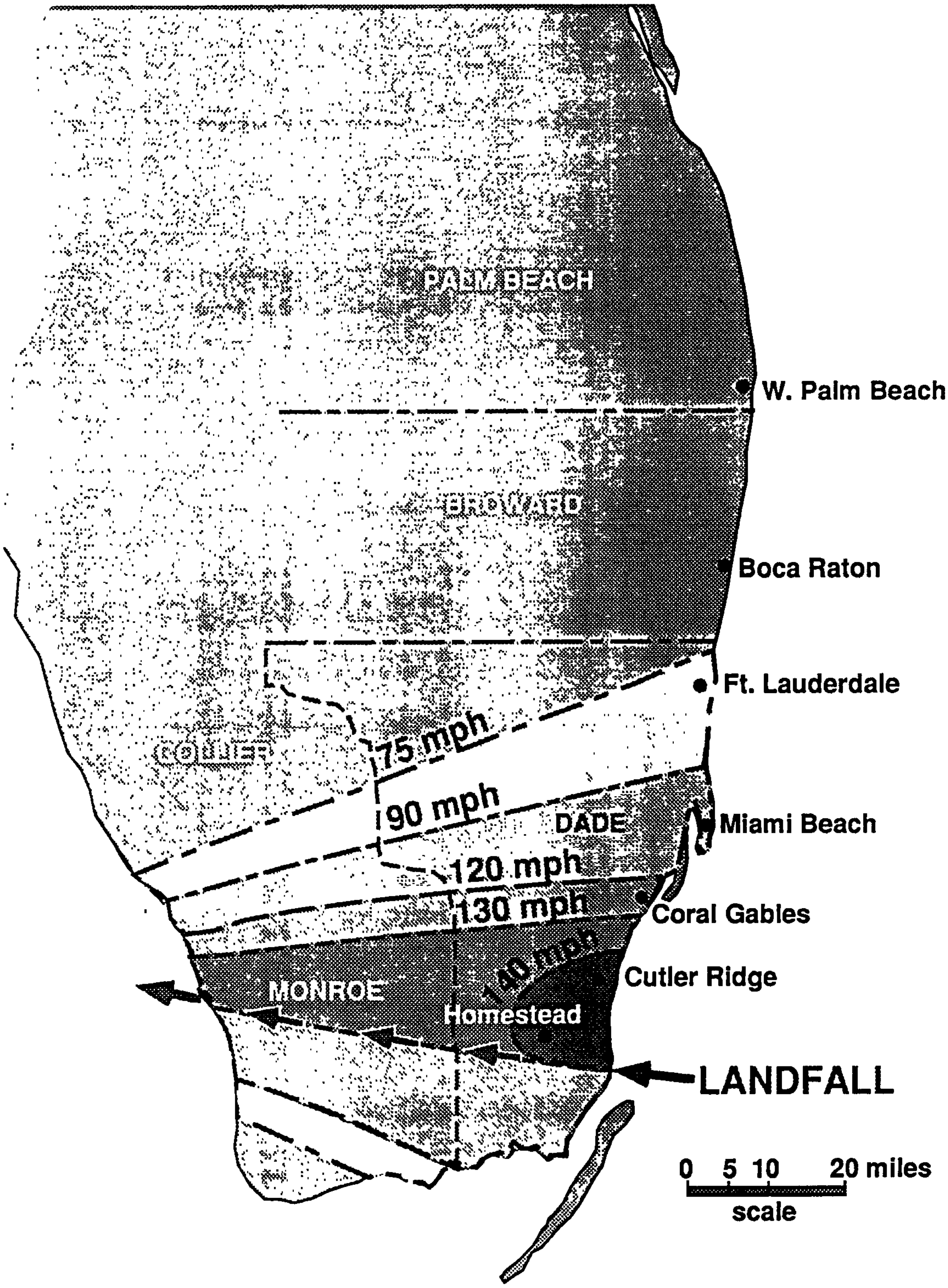

Fig. 12. Wind intensity contours of Hurricane Andrew.

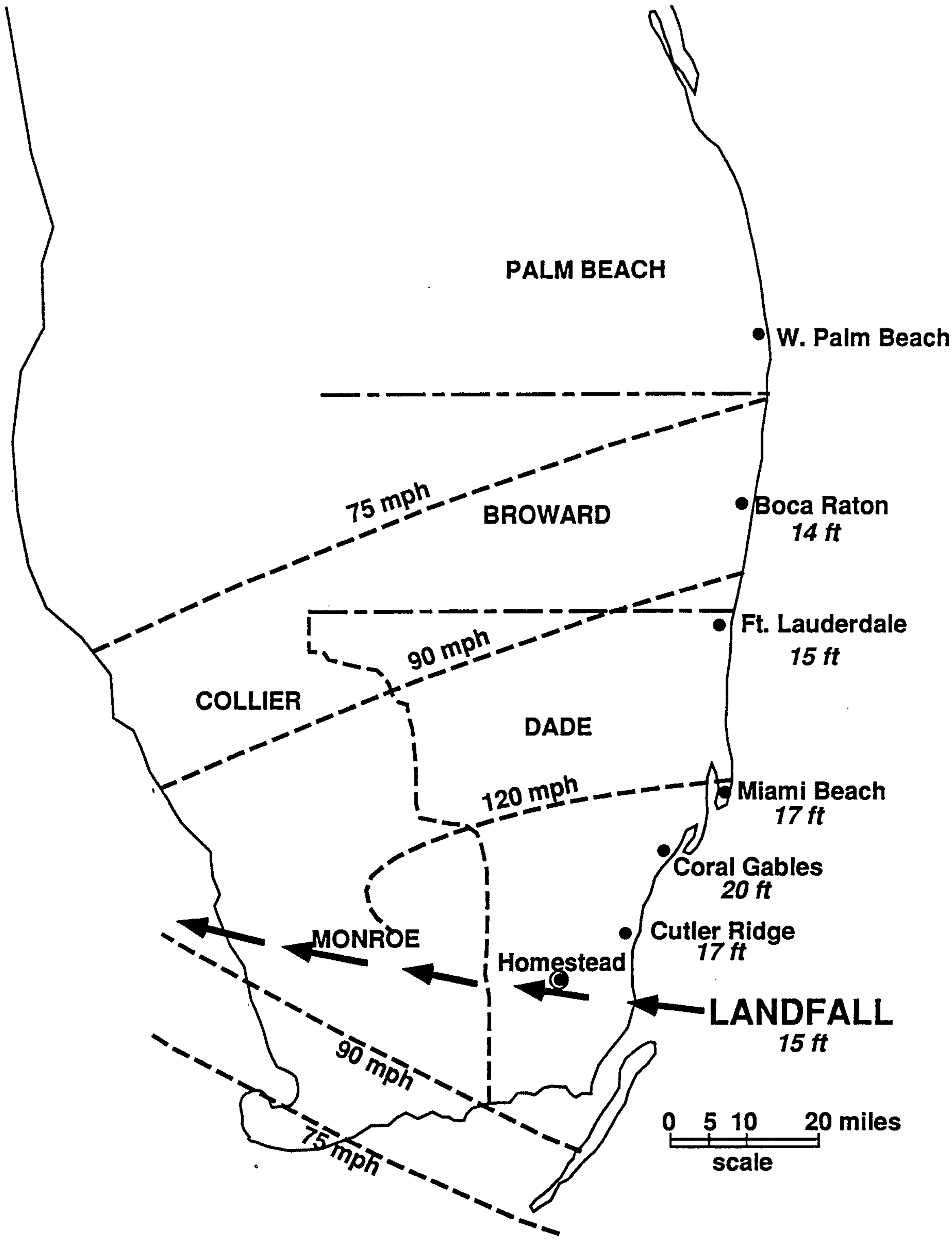

Fig. 54. Wind field and highwater elevations corresponding to Hugo being superimposed at eh landfall location of Andrew.

wind-induced damage would not be as devastating in the high intensity zone as Andrew's, the damage would certainly spread to a much larger area. Since utility poles, signs and trees would fail at lesser wind strength one would expect considerably heavier damage directly or indirectly related to these failures.

Conclusions and Recommendations

Conclusions

The damages caused by Hugo and Andrew were disproportionally high when compared with hurricanes of similar strength to hit the United States in the past. Extensive damage to residential type structures clearly is the main factor contributing to this high cost.

Hugo inflicted very severe water damage on residential structures along the coastal belt over one hundred miles in length. This was a consequence of high storm surge and lingering storm wave attacks. Most of the structural failure was due to insufficient structural elevation and inadequate foundation. Wide beaches and high dunes are definitely beneficial to dissipate wave energy provided the storm surge level is not significantly higher than the dune elevation. For extremely high storm surges such as experienced in Hugo, this beneficial effect vanishes quickly. It was not surprising that most of the older structures sustained heavier damage; damage to newer structures can largely be attributed to questionable construction and poor workmanship. Well-engineered and/or well-constructed structures survived with little or no damage. Most of the coastal protective structures were ineffective for their intended purpose, owing to lack of proper engineering.

In the region affected by Hugo, wind intensity seldom exceeded the design conditions. Although concerns about design code have been raised, most of the wind-related damages can be attributed to construction deficiency and other indirect causes such as fallen trees, signs and other foreign objects. The overall structural damage directly attributable to wind appeared to be less than in recent hurricanes of comparable strength.

In Andrew, wind intensity exceeded the design wind conditions over a region with a high concentration of low- or moderate-cost residential housing. The consequence appeared to be devastating. However, one should proceed cautiously to avoid hasty action in revising the design code. It may prove to be unnecessary and the action alone would certainly not be sufficient to prevent the same disastrous consequence in the future. Currently, the design wind speed in the coastal region of south Florida is higher than inland regions as well as most of the coastal communities affected by Hugo. Yet, there is no evidence that the structures are constructed differently in those regions to reflect the differences of design wind speeds. As a matter of fact, some of the newer structures presumably constructed in conformance with the code would not have survived in much lower wind speed. Therefore, one must first insure that the structures are properly constructed and inspected to meet the code standards.

Roof system is clearly the weakest link in preserving structural integrity. Framed walls and un-reinforced masonry walls are also prone to failure; the former failed largely due to inadequate connections and the latter due to insufficient shear resistance.

Modular homes generally performed better than on-site construction owing to superior structural member connections under controlled environment. Manufactured homes, on the other hand, fared miserably owing to substandard building materials. Mobile home foundation is not a major factor contributing to failures although foundation shifting is common. The defect can be easily corrected. Therefore, there is no fundamental engineering difficulty in the concept and design of mobile homes for hurricane zones even though there is no dispute that the current code governing manufactured homes is grossly inadequate and should be revised.

Finally, if Hugo were replacing Andrew the total damage to south Florida would almost certainly be higher than currently incurred as water related damage would be far more extensive and wind related damage would not be reduced. If Hugo were replaced by Andrew the overall cost of damage would mostly likely be less owing to the reduced water damage and the much smaller wind damage zone. From the statistical point of view both Hugo and Andrew are 25-year events in south Florida and 100-year events in South Carolina. Therefore, the chance of occurrence of each event is almost equal. To mitigate future losses one must consider both water- and wind-related damages when deciding proper corrective measures.

Recommendations

Structures built on the open coast should be designed to avoid water force rather than resisting it. Deep pilings are the only type of foundation to perform consistently. Protective structures are special structures and should be engineered by qualified personnel. These structures, owing to their important function, should be regulated much the same as buildings in terms of engineering, code enforcement and inspection.

Before raising the standards in building codes, the current construction practice should be thoroughly re-examined including roof material and structure, wall material and connections. The often disastrous failures caused by broken windows and doors suggest that shutters and/or reinforcements are essential in future constructions or retro-fittings.

Manufactured homes should not be hastily banned although current code inevitably has to be revised. In general, structural elements and systems assembled under controlled environment perform better than on-site construction.

One of the major problems both in Hugo and Andrew is the evident lack of quality control and lax of inspection. The lax of inspection will persist as long as the current development continues and the resources of local government are limited. It appeared that damage could have been significantly reduced if some of the minor but prevalent defects were corrected. The public will be better served if the engineering community can produce a user-oriented inspection manual for property owners.

Acknowledgement

Messrs. Ryuichro Nishi and Darwin Stubbs have assisted in damage surveys after Hurricane Andrew. Mr. Nishi also provided photographs and newspaper clips for this article.

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