HURRICANE FRAN EFFECTS ON COMMUNITIES WITH AND WITHOUT SHORE PROTECTION: A CASE STUDY AT SIX NORTH CAROLINA BEACHES

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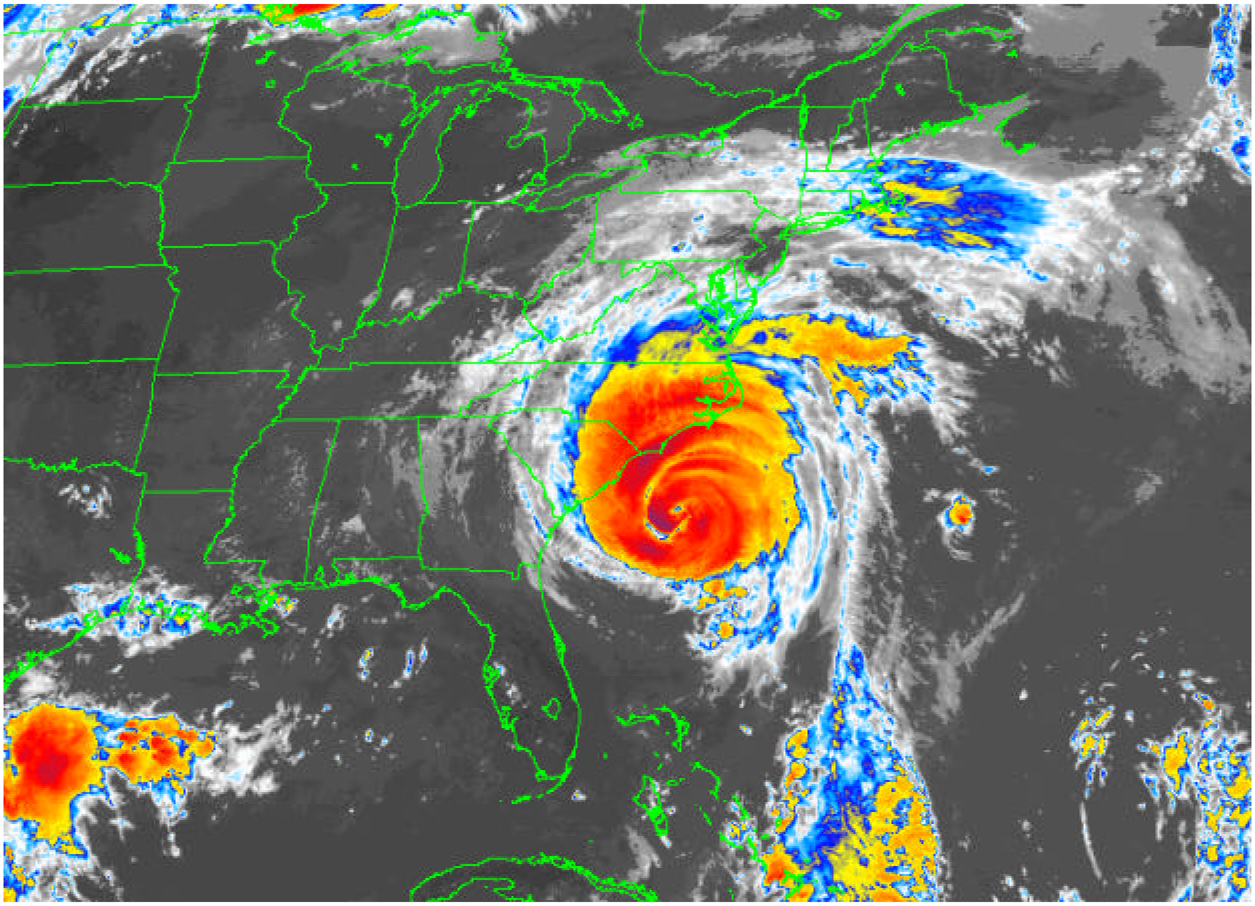


PREFACE

This report presents the findings and conclusions of a task force review of four areas along the North Carolina coast, which were impacted by two hurricanes during the summer of 1996. Two of the areas were protected by Corps shoreline protection projects and two were not.

The primary mission of the study was to determine if the presence of the Corps projects had a measurable impact on damages experienced during the storms. In order to accomplish this goal, the demographics of the study area were examined together with the damages sustained to determine the economic impacts. It was also necessary to study the physical setting of the areas to ascertain what impact the variances in the winds, storm surge, waves and geology had on any difference in storm damages.

A limited scope study was initiated in November of 1996 through the Policy and Special Studies Program of the Institute for Water Resources in cooperation with the Policy Division in Headquarters, United States Army Corps of Engineers. In recognition of the importance the study, in 1997 the scope was expanded and additional funding was received through Research and Development. Meetings were held in Duck, NC in July 1997, in the Wilmington District in October 1997 and again in September 1998, in the Norfolk District Office in March 1999 and at the Institute for Water Resources in April 2000.

ACKNOWLEDGEMENTS

In recognition of the importance of this study, a task force of U.S. Army Corps of Engineers personnel was formed under the leadership of Charles B. Chesnutt of Engineering Division, Civil Works. Other members of the original task force were Harry M. Shoudy from the Planning and Policy Division of Civil Works, James T. Jarrett of the Wilmington District, Thomas W. Richardson of the Engineer Research and Development Center, and Christine M. Brayman and Theodore M. Hillyer of the Institute for Water Resources.

Other major contributors included William J. Cleary, who provided the section on geology, under contract through the Wilmington District; and Robert E. Jensen who provided the section on Waves, Norman W. Scheffner, the section on Surge, and Todd L. Walton, the section on winds, all from the Engineer Research and Development Center.

In addition, many other Corps employees played a major role in the support and development of this report. These individuals included Eugene Z. Stakhiv and Robert A. Pietrowsky from the Institute for Water Resources who provided leadership and funding support. From the Civil Works Directorate in Headquarters, USACE early study effort through the Policy Studies Program was provided by Janice E. Rasgus and David B Sanford, Jr. provided over all leadership and was instrumental in the early expansion of the study effort. From the directorate of Research and Development, David B. Mathis provided early monetary support. Also deserving of recognition is Douglas L. Quinn of the Wilmington District who provided valuable assistance in the gathering of economic data.

Special recognition needs to go three individuals. First to James T. Jarrett of the Wilmington District who not only was the chief study advisor with on site knowledge of the study area, but also provided the section on high water marks and beach profiles. Second, to Dianne R. Dunnigan from the Institute for Water Resources who, when additional study management was needed, provided the additional effort necessary to assist in the successfully study completion. Third to Harry M. Shoudy of the Planning and Policy Division, Civil Works who had the early vision, following Hurricanes Bertha and Fran, that a case study which compared areas protected by Corps projects to those areas not protected, could produce a valuable lessons learned document.

The report was reviewed by many individuals, both inside and outside of the Corps of Engineers. Outside reviews were solicited from towns and counties in the study area, the State of North Carolina and the office of Region IV of the Federal Emergency Management Agency. Appreciation is expressed to all of those providing comments.

The spectacular picture of Hurricane Fran used in this report was pulled from the web site of the National Weather Service, National Oceanic and Atmospheric Administration, Department of Commerce, our thanks to this organization.

EXECUTIVE SUMMARY

A. INTRODUCTION

Coastal North Carolina was impacted by two very powerful hurricanes in the summer of 1996, Hurricane Bertha (a category 2 storm) on 12-13 July and Hurricane Fran (a category 3 storm) on 5-6 September. These storms hit areas protected by Corps shore protection projects (Carolina Beach and Wrightsville Beach) and areas not protected by Corps shore protection projects (Kure Beach and on Topsail Island, the three communities of Topsail Beach, Surf City and North Topsail Beach). This natural phenomenon presented an ideal opportunity to examine the value of Corps shore protection projects. In order to accomplish this study, Corps of Engineers experts from Headquarters, the Wilmington District, Engineer Research and Development Center and the Institute for Water Resources joined forces. Outside consultants were also used in the study and to review results. The study looked at the physical parameters of the storms (winds; storm surge and waves (which were modeled); and high water marks) as well as the offshore geology of the area to determine if these played a role in the storms relative impact on the communities. Finally, an economic damage assessment was performed of the impacted areas, included the collection of demographic information. While two storms hit the area, and some of the data collected and modeled compared the results of Bertha versus Fran, this report focuses on the last, and the most powerful of the storms, Fran. The following paragraphs summarize the results of this "case study."

B. FINDINGS

1. Winds. Sources of information for this portion of the study (Internet, National Hurricane Center, National Climatic Data Center, and Air Force) were accessed. From these sources, wind data were gathered, hand edited, and plotted. A number of onshore wind sites exist within a 100-mile radius of Wilmington, which gathered a variety of wind information. Data recording was sporadic during most of the periods of interest (i.e., two days before landfall and one day after landfall of the storms). Additionally, due to the gradients of the wind in the storms, only records reasonably close to the beaches were used. Because of the dramatic reduction of wind when the storms came ashore (i.e., friction effects), only three onshore recording stations were used (Myrtle Beach, SC, Wilmington, NC and

Winds Findings:

- ***Based on the best available wind speed data, the overall onshore wind speed patterns were not significantly different for the four beach areas, although slightly higher winds did exist at the southern beaches of Kure-Carolina-Wrightsville, than at the northern end of the study area (Topsail Island).***
- ***Differences in winds can not explain the differences in damage experienced by the protected areas of Carolina Beach and Wrightsville Beach and the unprotected areas of Kure Beach and the three communities on Topsail Island.***

New River, NC). Offshore recording towers were at Frying Pan Shoals (about 50 miles south southeast of Wilmington) and at Cape Lookout (approximately 45 miles northeast of North Topsail Beach).

2. Storm Surge. The storm surge portion of this investigation required specification of topography and bathymetry in the study area, modeling of the wind and pressure fields associated with the two hurricanes and the numerical modeling of the storm surge associated with each event. The storm surge model used in this study was the Advanced CIRCulation (ADCIRC) hydrodynamic model. The wind field model used in conjunction with the ADCIRC was the Planetary Boundary Layer (PBL). The PBL model computes a stationary wind and pressure field distribution corresponding to hurricane parameter input computed from the NOAA National HURricane Center's DATabase (HURDAT) of tropical storm events.

Storm Surge Findings:
- ***While surge elevations did not vary greatly over the study area (a maximum of 1.2 feet), elevations were highest at the protected Wrightsville Beach and lowest at the unprotected communities on Topsail Island.***
- ***Differences in storm surge can not explain the differences in damage experience by the protected areas of Carolina Beach and Wrightsville Beach and the unprotected areas of Kure Beach and the three communities on Topsail Island.***
- ***Hurricane Fran occurred at low tide. Had it occurred at high tide, damages would have been greater.***

3. Waves. The wave portion of the study was also modeled, using the results obtained from the storm surge simulation and the wave modeling technologies of WAve Model (WAM) and STeady WAVE (STWAVE). The wave modeling effort was performed in two stages; first WAM for the basin, region, and sub-region scales of the project; and then STWAVE coupled to the surge estimates generated by ADCIRC. Wind speeds were generated by Oceanweather, Inc. using a combination of atmospheric models, buoy, ship observations, satellite, and aircraft reconnaissance through-flights carried out by the Air Force as well as research flights performed by NOAA.

Waves Findings:
- ***While significant wave height, peak wave period, and offshore wave height did not vary greatly, the hightest readings were at the protected Wrightsville Beach and the lowest readings were at the unprotected Topsail Island areas.***
- ***Differences in waves can not explain the differences in damage experienced by the protected areas of Carolina Beach and Wrightsville Beach and the unprotected areas of Kure Beach and the three communities on Topsail Island.***

4. High Water Marks. The Federal Emergency Management Agency recorded high water marks from the southern end of Kure Beach to New River Inlet. These high water marks included surveyed marks left on the inside and outside of buildings as well as debris lines. Some marks inside and outside of buildings were

closer to the ocean than others, i.e., front row versus 2nd and 3rd rows, etc. While in general marks left on the inside buildings are more reliable, all observed high water marks were plotted to develop a trend, based on a straight arithmetic average of all high water marks. The highwater mark trend is as follows:

Area	Elevation (ft., NGVD)
Kure Beach	14.0
Carolina Beach	10.4
Wrightsville Beach	10.5
Topsail Beach	10.0
Surf City	8.9
North Topsail Beach	9.2

High Water Marks Findings:

- ***Excluding Kure Beach, the trend of the high water mark was not significantly different over the study area and followed the computed storm surge elevations, with the highest being at the protected Wrightsville Beach and the lowest at the unprotected Topsail Island Communities.***
- ***Except for the damage experienced at the southern end of Kure Beach, differences in high water marks can not explain the differences in damage experience by the protect areas of Carolina Beach and Wrightsville Beach and the unprotected areas of Kure Beach and the three communities on Topsail Island.***

Except for Kure Beach, the ocean beach areas impacted by Hurricane Fran consisted primarily of low barrier islands with varying dune sizes and dry beach widths fronting the dunes. The general elevation of the barrier islands landward of the dunes ranges from around 4 to 8 feet above NGVD. Kure Beach, which is actually a mainland beach, has ground elevations ranging from around 10 to 15 feet above NGVD. The difference in ground elevation between Kure Beach and the other beach areas impacted by Fran may have contributed to some of the differences in high water marks observed in the area. For the low lying barrier island, the storm surge combined with the storm waves, overtopped the beach and flowed across the islands into the bays on the back side of the islands. At Kure Beach, the high landmass prevented general overtopping and may have created a partial standing wave along the entire beachfront as water was trapped and piled up between the nearshore bar and the beach.

5. <u>Geology</u>. To accomplish the objects of the geologic section, critical databases (i.e., seismic, sidescan, vibracore, and surface sediment, etc.) were integrated from the shoreface with data from each of the shoreline reaches. The study sites consist of both headland and barrier segments for which there are a variety of onshore and offshore data. Various levels of quality, completeness, and interpretation characterize these data. Sidescan sonar and high-resolution seismic surveys are available for the offshore portion of most of the study sites. Some of the sidescan sonar and seismic data exist in GIS coverage that has been used to define salient morphological features and the specific nature of the shoreface. Key elements that aided interpretation of the remotely sensed data are extensive diver seafloor observations, vibracores, and "field" maps describing the shoreface. From these data, mosaic maps of the seafloor, geologic facies maps, geologic cross sections, morphological maps of the shoreface and 3-dimensional models for some of the study sites were generated.

Geology Findings:
- ***Offshore geology varies from Kure Beach to Topsail Island and contributed to differences in prestorm beach conditions. The areas with existing wide beaches and dune systems, either man-made or natural, experienced less storm damage.***
- ***The high water marks observed at the southern end of Kure Beach were believed to be due to a combination of high landmass that produced some wave standing and localized wave phenomena due to submerged Coquina rock outcrops.***
- ***The prestorm condition of the beach helps to explain the lesser damages at the protected areas and greater damages at the unprotected areas.***

6. Economic Damage Assessment.

a. Overview. For this study an analysis of economic damages in the study area was conducted. Demographics for the study area were also collected. The sources of data were the Wilmington District of the Corps of Engineers, the Federal Emergency Management Agency (FEMA), local town and county managers, and building inspectors. In this report, Federal Insurance Administration (FIA claims for damages to structures, personal property and land were compared in the areas that had a shoreline protection project to those areas that did not when Hurricane Fran struck in September 1996. This is different from a typical Corps planning report that calculates a benefit to cost ratio and maximum net benefits. “Benefits” of the existing shoreline protection projects, per se, were not calculated in this particular study; nor were “damages prevented.” Both of these measures involve measuring hypothetical situations and were not considered appropriate for this study.

b. Land Area and Population. The Greater Wilmington area, which encompasses a significant portion of the report study area, has been and still is one of the fastest growing areas in the country. The beaches under investigation in the study are located in three counties, Hew Hanover County (Kure, Carolina and Wrightsville Beaches), Pender County (Topsail Beach and a portion of Surf City) and Onslow County (with the remainder of Surf City and North Topsail Beach). The total land area of these three counties is 1,837 square miles; the total land area of the six communities is 28.7 square miles. Census statistics for population and economic activity of these beach communities are greatly understated as the Census only takes into account permanent residents of the area. In addition to permanent residents, there are two categories of seasonal population; they are "summer population" and "day trippers." Summer population includes those on overnight to extended stays in both houses and motels. Day trippers are defined as visitors from the local area. New Hanover County is the smallest but most densely developed and, outside of the three beach communities and the city of Wilmington, is unincorporated. Pender County, abutting

New Hanover County on the north, is though of as a bedroom suburb of Wilmington and has experienced the greatest growth of the three counties in the study area because of the availability of undeveloped property. Most of this county is unincorporated except for a few small towns. Onslow County, adjacent to Pender County on the north contains the city of Jacksonville and the Camp Lejeune Marine Corps Base. The estimated 1996 population, permanent county density and the estimated 1996 additional summer population and day trippers are provided in the following table.

Study Area Population

County	Town	1996 Population	1996 Density (persons/sq. mile)	Summer Adds Day trippers
New Hanover		143,430	721	n/a n/a
	Kure Beach	738	923	7,000 2,000
	Carolina Beach	4,690	2,759	13,000 25,000
	Wrightsville Beach	3,165	2,435	10,000 35,000
Pender		35,978	41	n/a n/a
	Topsail Beach	434	87	7,000 1,000
	Surf City	810	172	9,000 n/a
Onslow County		150,216	196	n/a n/a
	Surf City	337	674	Included in the Pender portion
	North Topsail Beach	1,091	74	14,000 3,000

n/a = not available
Sources of data: U.S. Census; North Carolina Office of State Planning; and CAMA (North Carolina Coastal Area Management Act) Land Use Plans.

c. Housing. The study area has a wide variety of housing including both single family and multiple occupancy, ranging from smaller traditional beach cottages and mobile homes to luxury homes and high rises. Prices range from less the $100,000 to millions of dollars. Wrightsville Beach is the most affluent of the six communities in our study area and is the closest geographically to a major city (Wilmington). Because the greater Wilmington area is experiencing tremendous growth, housing prices throughout the study area continue to escalate, driven by demand, though differing county to county. Median house values from the

> "From 1994 to 1995, local realtors estimated that housing costs jumped as much as 14 percent on qverage with an increase of as much as 20 to even 40 percent in upscale communities." (p349), *The Insiders' Guide to Wilmington & North Carolina's Southern Coast*.

1990 U.S. Census for the communities are grossly underestimated compared to 1996 values. Values have increased 200 to 300 percent since the 1990 Census. However, in order to provide a comparison and using the best available numbers, the number of housing units per area and the median 1990 value are provided in the following table. Also provided are the tax rates. Note that town tax rates shown are in addition to the county tax rate.

Housing Statistics

County(s)	Town	Housing Units (1990)	Median Value ($) (1990) [a]	1996-97 Tax Rate/($1000)
New Hanover		57,076	72,000	0.645
	Kure Beach	937	81,000	0.390
	Carolina Beach	3,342	80,000	0.400
	Wrightsville Beach	2,413	192,000	0.235
Pender		15,437	60,200	0.650
	Topsail Beach	998	149,000	0.270
Pender/Onslow				
	Surf City	2,242	98,900	0.450
Onslow		47,526	62,200	0.644
	North Topsail Beach	2,173	Na	0.290

Source: U.S. Census. [a] Owner-occupied

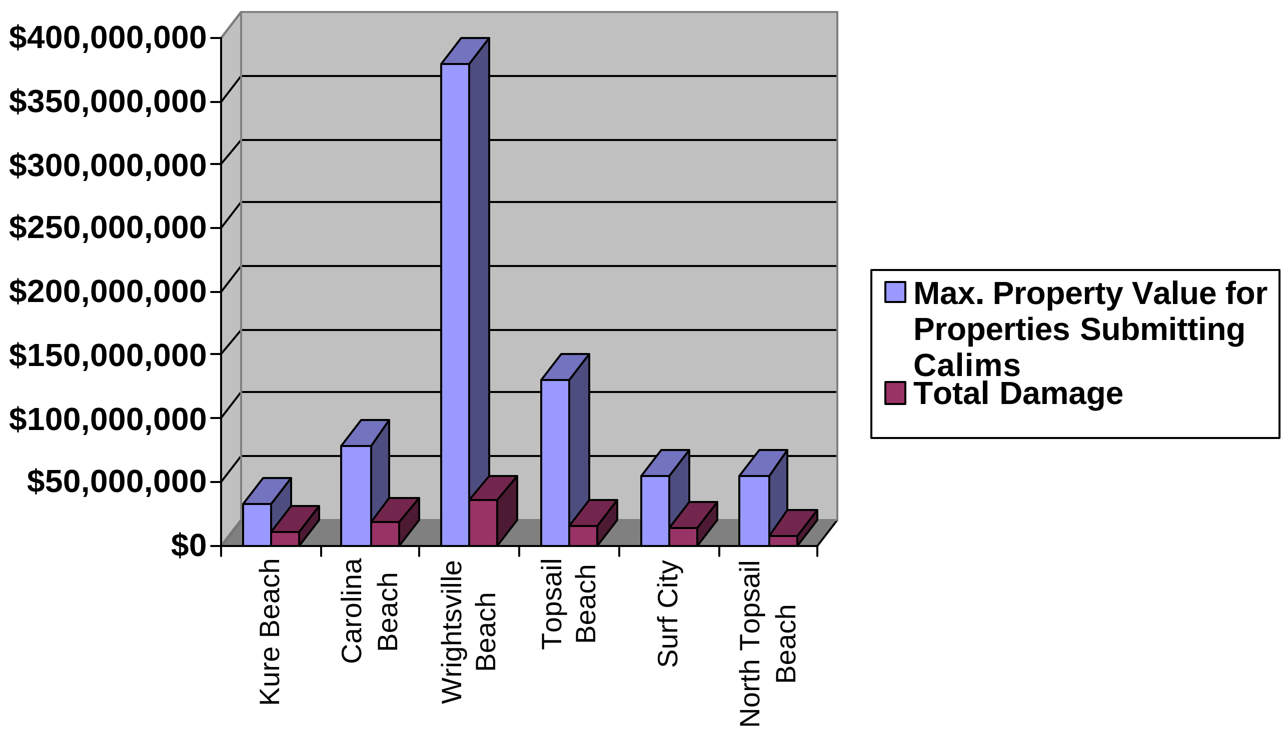
d. Damages Overview. An economic damage assessment to ascertain storm effects at the areas that were not protected by Corps projects (Kure Beach and Topsail Island) in comparison with those two that were protected by Corps projects (Carolina Beach and Wrightsville Beach) for Hurricane Fran was performed. The primary focus was on the comparative analysis between protected and unprotected areas rather than an absolute quantitative analysis. Comparison of damages was done by examining total damage based on FIA claims in the communities compared to the communities' total property bases. Damages were further analyzed to compare differences in oceanfront properties for those communities protected by Corps shoreline protection projects to those not protected. FIA claims were the primary source of damage data. Other sources were interviews with local community officials, FEMA Damage Survey Reports and *Building Performance Assessment* report, and North Carolina Coastal Area Management Act (CAMA) land use plans. FIA claims are useful when evaluating damage due to the absence or presence of a shoreline protection project because flood insurance covers damage caused by storm surge, wave wash, tidal waves or overflow of any

> "Expect to pay an average of $500,000 for virtually any single-family home [in Wrightsville Beach] and don't be surprised by much higher prices, since the available land is all but exhausted in terms of development on the island...Homes can be purchased for as low as $80,000 and can rise to a half-million dollars along Carolina Beach, Wilmington Beach, Kure Beach and Fort Fisher...Unlike the decidedly pricier beaches to the south, Topsail Island offers homes for $100,000 or less in some cases. New 2,000-square-foot homes can cost as much as $250,000 to $300,000 on the ocean, although there are not yet many homes this large on the island. The norm is more 1,500 to 1,800 square feet, and prices average $175,000 to $200,000" (p. 358-360, *The Insiders' Guide to Wilmington & North Carolina's Southern Coast*).

body of water from above-normal cyclical levels. FIA flood insurance does not cover property damage caused by wind-driven rain entering a home or business through openings in the roof or walls. Rainwater and wind damage from a roof, window or wall opening would, in most cases, be covered by standard homeowners' policies. Because of this exclusion of wind and rain damage from flood insurance policies, this study does not overestimate damages that could be prevented by a shoreline protection project.

e. Damages by Community. Because of the difference in demographics (median house value, number of housing units, land area, etc.) of the various beach communities, it is more appropriate to compare percent damages, which normalizes the damages, as opposed to absolute damage numbers. The property values versus damages claimed are shown in the following figure.

Property Values Versus Damages - Hurricane Fran



Topsail Island and Kure Beach, both unprotected areas, sustained a greater percentage of damage than did Wrightsville Beach and Carolina Beach where there were shoreline projects. The shoreline protection project at Wrightsville Beach is 14,000-feet in length. The "Wrightsville Beach" community includes not only the area behind the Corps project, but also the northern end of Wrightsville Beach (Shell Island), Harbor Island and mainland Wrightsville Beach.

f. Structures Destroyed. Perhaps one of the most telling statistics is the number of structures destroyed. This is because the structures were largely destroyed by erosion and wave runup. This is the type of damage a shoreline protection project is designed to prevent, but the presence of a shoreline protection project does not guarantee the absence of damages in a community. Often flooding comes from back bay sources that cannot be prevented by an oceanfront shoreline protection project. Because the examined communities are barrier islands, they all experienced flooding from the sounds and rivers [Intracoastal Waterway] located between the islands and the mainland. Wrightsville Beach had no structures destroyed. Carolina Beach had only twenty structures destroyed (only two of which were oceanfront) and it is the community with the largest number of housing units. Both of these communities had a Corps shoreline protection project protecting them. The number of structures destroyed is shown in the following table.

> "While Hurricanes Bertha and Fran caused damage to many structures at Wrightsville Beach, such damage did not result in the total destruction of any buildings or lots within the Town." *1996 CAMA Land Use Plan: Town of Wrightsville Beach, NC*

Structures Destroyed and Claims Paid

Item	Kure Beach	Carolina Beach	Wrightsville Beach [1]	Topsail Beach	Surf City	North Topsail Beach [2]
# of Structures Destroyed [3]	20	20	0	30	70	320
# of FIA Claims	157	758	1,415	781	710	363
# of FIA Claims Paid	128	676	1,203	664	522	273
Average Value Claim Paid	$78,672	$22,111	$25,171	$19,368	$21,427	$134,348

Footnotes:
[1] The designation "Wrightsville Beach" includes not only the 14,000 foot long shore protection Wrightsville Beach project but also mainland Wrightsville Beach, Harbor Island or the northern part of the island of Wrightsville Beach (Shell Island). The project does not provide protection to these latter three areas.
[2] North Topsail Beach encompasses Coastal Barrier Resources Act (COBA) areas which cannot participate in the National Flood Insurance Program, and therefore, flood insurance is not available. Because of this lack of claims is *not* an indication of lack of damages.
[3] Based on interview with local officials. Of the 20 structures destroyed in Carolina Beach, only two were on the oceanfront. It is important to note that of the hundreds of structures destroyed in Topsail Beach, Surf City and North Topsail Beach, many of these were not oceanfront and could have been destroyed if shore protection projects had been provided.

g. Oceanfront Property. The following table examines claims only for oceanfront properties, which is part of the above aggregated data. As expected, the difference in percent of property damaged is even greater for oceanfront properties than properties in the communities as a whole. This reinforces the concept that shoreline protection projects provide damage prevention from surge and wave runup.

Oceanfront Damages and Claims

Item	Kure Beach	Carolina Beach	Wrightsville Beach [1]	Topsail Beach	Surf City	North Topsail Beach [2]
Oceanfront Damage [3]	$1,047,710	$2,432,973	$320,586	$5,572,490	$7,974,939	$3,564,484
Maximum Property Damage [3]	$3,163,440	$21,967,852	$2,967,852	$29,166,794	$30,327,978	$19,168,391
Damage Value Ratio	33%	11%	13%	19%	26%	19%
# of claims	12	85	13	200	231	131

Source: Federal Insurance Administration claims database for the Hurricane Fran event.
[1]. The Corps project is 14,000-feet in length and does not cover the north end of the island (Shell Island).
[2]. Many structures in North Topsail Beach are not eligible to be in the NFIP because they are in COBRA areas.
[3]. For properties submitting claims.

h. Complexities with Economic Data. Each locality is unique with respect to protection from storms, value and age of structures, amount of oceanfront versus shoundside, etc. For example, to examine all the FIA data in Wrightsville Beach and credit it to a "protected shoreline project" is not accurate. First, the north end of Wrightsville Island (Shell Island) is not protected by a Corps shoreline protection project. This area is characterized by newer housing (less than 30 years old) with large single family homes and multi-family high rise complexes. Harbor Island and mainland Wrightsville Beach are also not directly protected by the shoreline protection project. Of the 1,203 paid claims for the town of Wrightsville Beach, about 340 were in the vicinity of the shoreline protection project. Damage assessment in North Topsail Beach is particularly problematic because of the town contains COBRA areas where flood insurance is not available. Much data, therefore had to be gathered by talking with local officials. Federal Flood Insurance Claims are invaluable when evaluating damages and damage prevention due to the presence of absence of a shoreline protection project because flood insurance covers damage caused by storm surge, wave wash, tidal waves or overflow of any body of water from above-normal cyclical levels. Unfortunately, much of the FIA data are incomplete, often having no entry or an entry of "9999" for data fields that would allow an even more comprehensive analysis. Lack of FIA data was found in such fields as lowest floor elevation, base flood elevation, differences between lowest floor and zero damage elevations, building water depth, foundation type, wall construction and surface, flood characteristics, and hours water was in the building. These are valuable additional pieces of information and the Corps of Engineers partnering with FEMA and FIA in post storm damage surveys would pay dividends.

Economic Damage Assessment Findings:

- ***In terms of demographics, Wrightsville Beach and Carolina Beach are more densely populated and have higher housing values than Kure Beach and the three beach communities on Topsail Island.***
- ***The three communities on Topsail Island and Kure Beach, all unprotected areas, sustained a greater percent of damages than did the protected areas of Wrightsville Beach and Carolina beach.***
- ***No structures were destroyed at the protected Wrightsville Beach while hundreds were destroyed in the unprotected areas of Topsail Island.***
- ***Protected Carolina Beach and unprotected Kure Beach both had the same number of structures destroyed, but Carolina Beach is much more developed than Kure Beach and only two of the structures at Carolina Beach were on the oceanfront.***
- ***Claim and damage value was difficult to obtain and much of the FIA data were incomplete. Corps partnering with FEMA and FIA in collecting after storm data would pay dividends.***
- ***If erosion and wave run-up were thoroughly evaluated in reporting of the claims, the differences between protected and unprotected areas would most likely be greater.***
- ***Lack of information prior to actual storm events was the largest deficiency to accurate***

C. CONCLUSIONS

- The areas protected by Corps of Engineers shore protection projects (Wrightsville Beach and Carolina Beach) received less damage as a percent of total property value than did the unprotected areas (Kure Beach, Topsail Beach, Surf City and North Topsail Beach).
- While differences in physical storm parameters (winds, storm surge and waves) were observed from Kure Beach to North Topsail Beach, the differences were not large enough to explain the differences in damage. If anything, storm parameters showed the most severe part of the storm hit Wrightsville Beach and the less severe part of the storm hit Topsail Island.
- Offshore geology, which varies from Kure Beach to Topsail Island, likely contributed to damages and lack of damages.
    - At the south end of Kure Beach is a Coquina rock outcrop that contributed to the highest of the highwater observed at this location and resulted in an increase in damages.
    - The areas with existing wide beaches and a frontal dune system, either natural or man-made, experienced less storm damage.
- Partnering with agencies such as the Federal Emergency Management Agency and the Federal Insurance Administration in collecting damages data through post storm surveys and distinguishing between flooding and erosion damages would pay dividends.

D. SUMMARY

Beach nourishment projects similar to the ones at Carolina Beach, Wrightsville Beach and now at Kure Beach do reduce hurricane storm damages, which, in turn, reduce Federal disaster recovery costs.

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CHAPTER 1
INTRODUCTION

A. PURPOSE OF STUDY

Coastal North Carolina was impacted by two very powerful hurricanes in the summer of 1996, Hurricane Bertha (a category 2 storm) on 12-13 July and Hurricane Fran (a category 3 storm) on 5-6 September. These storms hit areas protected by Corps shoreline protection projects (Carolina Beach and Wrightsville Beach) and areas not protected by Corps shoreline protection projects (Kure Beach, Topsail Beach, Surf City and North Topsail Beach). This natural phenomena presented an ideal opportunity to examine the value of Corps shoreline protection projects. The report presents the results of this "case study." A description of the study area is provided in Chapter 2.

B. STUDY HISTORY

1. Original Study. A limited scope damage assessment study was initiated in November 1996 to investigate the beach areas of the lower North Carolina coast as a result of Hurricanes Bertha and Fran. The intent of the study at that time was only to compare the damages at those areas protected by Corps shoreline projects (Carolina and Wrightsville Beaches) against those areas not protected by Corps projects (Kure Beach and Topsail Island). In order to accomplish this task, a study was initiated under the auspices of the Policy Studies Program of the U.S. Army Corps of Engineers Institute for Water Resources in cooperation with the Policy Division of the Directorate of Civil Works in the Corps' Headquarters office.

2. Study Expansion. Recognizing the importance of this study, the effort was expanded in 1997 to collect the physical storm parameters of the two hurricanes, i.e., winds, storm surge and waves, as well as the geology of the offshore areas and the collection of high water mark data. This additional effort was undertaken to ascertain if it was these items that may have caused differences in damages at the beach communities under consideration rather than any man made modifications to the beaches. At this time an effort was also undertaken to collect data on "local and state benefits" (i.e., what is the value of the beaches to the towns, counties and the state), and on the "environmental setting." This data, however, was not included in the final assessment as the data was not readily available. It would of required several hundred thousand dollars to collect the data on "local and state" benefits and there was no reliable data on the before and after "environmental setting."

3. Study Conduct. A task force comprised of experts in shore protection from the U.S. Army Corps of Engineers was formed. Team members were from the Headquarters (HQUSACE), the Wilmington District, the Engineer Research and Development Center and the Institute for Water Resources. Meetings were held at Duck, NC on 17 July 1997, in the Wilmington District Office on 27-28 October 1997 and

again on 16-17 September 1998, in the Norfolk District on 22 March 1999 and at the Institute for Water Resources on 20 April 2000. Numerous technical writers and other support people assisted the basic task force. A list of the major contributors to the study is provided as **Appendix A**.

C. STUDY METHODOLOGY

1. Storm Physical Parameters.

a. Winds. This component of the study pertains to an evaluation of onshore winds near the North Carolina coast during Hurricanes Bertha and Fran. To address these questions, various sources of information (Internet, National Hurricane Center, National Climatic Data Center, and Air Force) were accessed. From these sources, wind data were gathered, hand edited, and plotted. A number of onshore wind sites exist within a 100-mile radius of Wilmington, which gathered a variety of wind information. Data recording was sporadic during most of the periods of interest (i.e., two days before landfall and one day after landfall of the storms). In many cases the data was of limited use due to equipment malfunctions during the wind extremes of the storms. Additionally, due to the gradients of the wind in the storms, only records reasonably close to the beaches were used. Because of the dramatic reduction of wind when the storms came ashore (i.e., friction effects), only sites in the near vicinity of the beaches were utilized to draw conclusions. Although numerous sites were initially investigated, only three primary onshore sites (Myrtle Beach, SC; Wilmington, NC and New River, NC) were utilized in drawing conclusions for this limited onshore wind study. For further discussion on winds see Chapter 3, Paragraph A.

b. Storm Surge. The storm surge portion of this investigation required specification of topography and bathymetry in the study area, modeling of the wind and pressure fields associated with the two hurricanes and the numerical modeling of the storm surge associated with each event. The storm surge model used in this study was the Advanced CIRCulation (ADCIRC) hydrodynamic model. Results of the study are presented as maximum water surface elevations at three sites (Kure Beach, Carolina Beach and Topsail Beach) and as a spatial distribution of maximum water level distribution along the coast. The storm surge portion of the report is provided in Chapter 3, Paragraph B.

c. Waves. The goal of this component of the study was to determine the impact of the coupling of surge and wave effects generated by the two hurricanes at the prescribed four locations. The assessment is based on results obtained from storm surge simulation using ADCRIC (see Chapter 3 Paragraph B) and wave modeling efforts using two modeling technologies, WAM and STWAVE driven by high resolution find fields. For further discussion on waves see Chapter 3, Paragraph C.

d. High Water Marks. A survey of High Water Marks was performed by the Federal Emergency Management Agency, see Chapter 3, Paragraph D. High water marks included all surveyed marks, i.e., marks left on the inside of buildings as well as debris lines. A trend line of these marks is provided as well as several photos of the damage caused by Hurricane Fran.

e. Beach Profile Changes. The Wilmington District recorded a number of beach profiles at Kure, Carolina and Wrightsville beaches, see Chapter 3, Paragraph E. These profiles provide both pre and post Hurricane Fran cross-sectional looks at various locations along the beach. Profiles are not provided along Topsail Island as there are no projects in this area.

2. Geology. To accomplish the objects of the geologic section, critical databases (i.e., seismic, sidescan, vibracore, and surface sediment, etc.) were integrated from the shoreface with data from each of the shoreline reaches. The study sites consist of both headland and barrier segments for which there are a variety of onshore and offshore data. Various levels of quality, completeness, and interpretation characterize these data. Sidescan sonar and high-resolution seismic surveys are available for the offshore portion of most of the study sites. Some of the sidescan sonar and seismic data exist in GIS coverage that have been used to define salient morphological features and the specific nature of the shoreface. Key elements that have aided the interpretation of the remotely sensed data are extensive diver seafloor observations, vibracores, and “field” maps describing the shoreface. From these data, mosaic maps of the seafloor, geologic facies maps, geologic cross sections, morphological maps of the shoreface and 3-Dimensional models for some of the study sites were generated. For the geologic setting of the study area see Chapter 4.

3. Economic Damage Assessment. For this study an analysis of economic damages in the study area was conducted. Demographics for the study area were also collected. The sources of data were the Wilmington District of the Corps of Engineers, the Federal Emergency Management Agency (FEMA), local town and county managers, and building inspectors. In this report, Federal Insurance Administration (FIA) claims for damages to structures, personal property and land were compared in the areas that had a shoreline protection project to those areas that did not when Hurricane Fran stuck in September 1996. This is different from a typical Corps planning report that calculates a benefit to cost ratio and maximum net benefits. “Benefits” of the existing shoreline protection projects, per se, were not calculated in this particular study; nor were “damages prevented.” Both of these measures involve measuring hypothetical situations and were not considered appropriate for this study. For a complete description of the economic damage assessment, see Chapter 5.

4. Findings and Conclusions. A summary of the report findings and conclusions are provided in Chapter 6.

5. Supporting Documentation. A list of supporting appendices is also provided.

CHAPTER 2
DESCRIPTION OF STUDY AREA

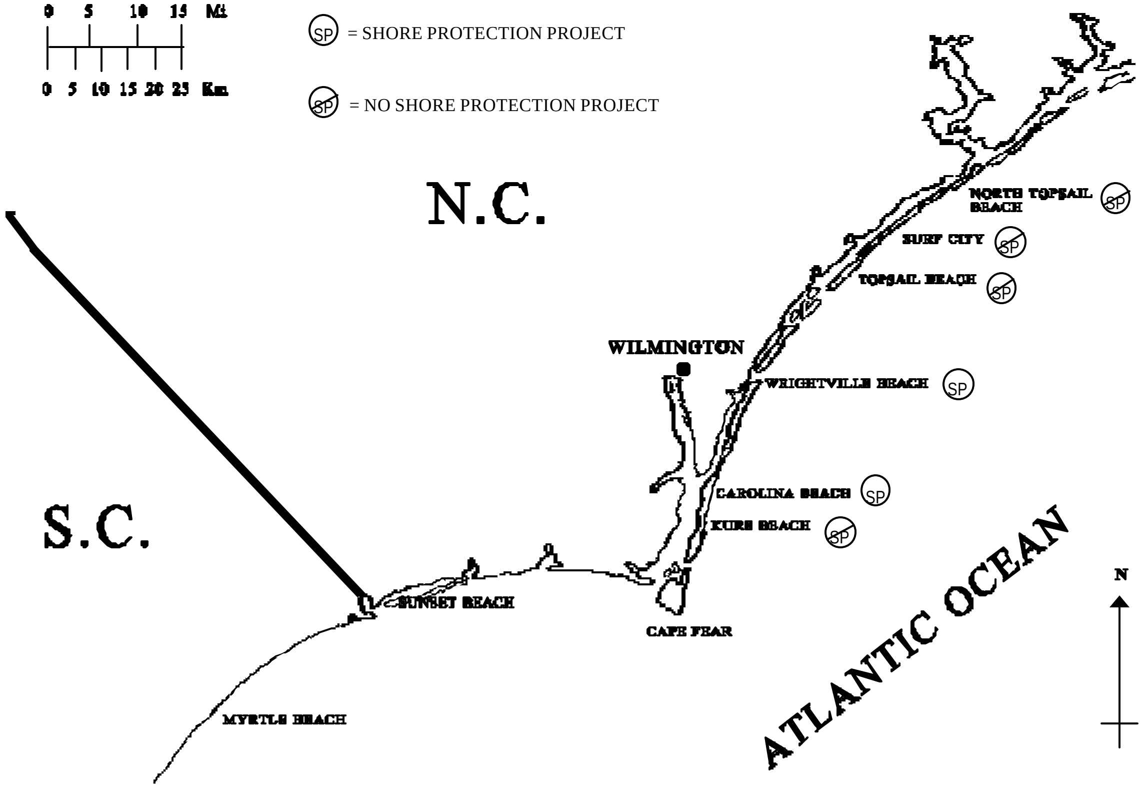
A. BACKGROUND INFORMATION

1. Study Area. The study area encompasses about 55 miles of the North Carolina coast from Fort Fisher, approximately 20 miles south of Wilmington on the south to North Topsail Beach, about 40 miles northeast of Wilmington on the north. Counties in the study area (from south to north) are New Hanover, Pender and Onslow. See **Figure 2-1** for a location map of the area. All study areas are on narrow barrier islands, most of which have dunes. Virtually the entire section is fronted by sandy beaches. Tidal ranges are moderate. Potential inland sources of sand are typically trapped in estuaries and bays. In the summer months, the islands are subject to hurricane type storms that come from a southerly direction and in the winter months by, often severe, storms out of the northeast. The beaches in this area are typical summer tourist destinations with the summer population greatly inflating the permanent population. While the population of the beach communities in the Wilmington area not as large as some of their coastal neighbors, with the completion of Interstate Highway 40 in 1990, the population of the area, both permanent and from summer tourism has risen significantly. The study area consists of three distinct project areas, on the south, Kure and Carolina Beaches, in the center, Wrightsville Beach, and on the north, on Topsail Island, the three communities of Topsail Beach, Surf City and North Topsail Beach. During the storms of 1996, Carolina and Wrightsville Beaches were protected by Corps shore protection projects while Kure Beach and the communities on Topsail Island were not.

2. Beach Processes.

a. Physical Setting. Shorelines of the United States cover a broad range of processes, geology, morphology, and land usage. There are five United States coastlines: Atlantic, Gulf of Mexico, Pacific, Great Lakes, and the Arctic. Although the processes of waves, water levels, tides, currents, and winds affect the coasts, they vary in intensity and relative significance. Variations in sediment supply and local geological setting result in coastal diversity. The North Carolina coastline is defined by a long, straight fine-sand beach, with intermittent wetlands and differs greatly from other shores that are defined by clay bluffs or rocky headlands. Not all shores are in equilibrium with the present littoral system. Shores with a character inherited from previous non-littoral process (i.e., glacial or deltaic materials) may experience significant rates of erosion under present conditions. Some shores exhibit short-term seasonal or episodic event-driven cyclic patterns of erosion and accretion. Other shores display long-term stability (balanced sediment supply and no relative sea level rise influences). Accretion and erosion are natural responses to the processes of the shore. Shores that have been heavily modified by the activities of man usually require a continuing commitment to retain a status quo. Additional specific information on the physical setting of the study area is given in Chapters 3 and 4.

Figure 2-1 Study Area



b. Engineering Aspects of Beach Fill and Nourishment.

(1). General. Extensive bodies of literature and case examples exist with respect to the protective values afforded upland developments by the presence of large natural coastal dunes and broad frontal beaches. Because of this, and the inherent natural values of beaches and dunes, most states have enacted laws that, in various ways, regulate developmental practices that could possibly degrade or otherwise adversely affect these natural features where they exist. In North Carolina, the state provides development regulations for the coast, for sand dunes, and for erosion control. Local regulations must meet state requirements. Federal guidance on planning and design for beach fills and dune construction, and all other types of shore protection measures, can be found in the *Shore Protection Manual*, U.S. Army Coastal Engineering Research Center, 1984, 2 Vols. and the more recently released EM 1110-2-3301, *Engineering Design of Beach Fills*, dated 30 June 1994.

(2). Basis of protective value. The scientific basis underlying the protective values of dunes and beaches is that they are extremely efficient land features in terms of their singular or combined capacities to dissipate and absorb wave energy. On the other hand, under the assault of storm-tides and attendant wave action, the high performance of these features in dissipating wave energy comes at the expense of their own erosion and degradation. This example of the value of beach protection was observed by a FEMA deployed Building Performance Assessment Team (BPAT) to Coastal North Carolina to assess damage caused by Hurricane Fran. The primary mission of the team was to assess the performance of buildings on the barrier islands most directly affected by Hurricane Fran and to make recommendations for improving building performance in future events. One site observation of the BPAT was that a[B]each nourishment with construction of a hurricane protection dune substantially reduced damage in Wrightsville Beach and Carolina Beach. In these areas, the manufactured dune eroded but prevented erosion failures and reduced wave damage to structures. Such dunes are considered expendable but require periodic maintenance and replacement after the worst storms.aaaHowever, if the sediment supply to the beach and dune system is adequate, the system will recover from storm effects in the interim periods between major storm events.

aBeach nourishment with construction of a hurricane protection dune substantially reduced damage in Wrightsville Beach and Carolina Beach.a
1996 FEMA BPA Team

(3). Natural storm-recovery of beach/dune system. The natural process of beach recovery can occur in a matter of days or weeks following a storm. However, the recovery or restoration process for dunes and the upper level of the beach strand takes months and involves the reestablishment of stabilizing vegetation as well as the re-accumulation of the sediment volume lost to erosion. The sediment supply for general beach recovery is provided by the adjacent shorelines and immediate offshore areas and is transported to the beach by post-storm wave action having restorative hydraulic characteristics. Most of the sediment supply involved in beach recovery comes from the pre-storm beach sediments that were displaced to the nearshore zone during the subsequent course of storm-tide and wave attack. When sediment supply to the beach is inadequate, erosion of the beach will be a persistent, rather than an intermittent, phenomenon. In that situation, the original beach will progressively narrow in width and the frontal dunes, being increasingly exposed to more frequent and intense wave attack, will eventually be lost to erosive processes. In a completely natural setting, an erosive condition is usually of little concern as the beach and dune system is simply reestablished in a more landward position. However, where substantial reaches of the shoreline have been developed or a valuable natural resource is threatened by a naturally eroding process, protective measures may be necessary. In the past such problems were often addressed by construction of groins and seawalls. Since the 1960s, however, erosion problems are increasingly being addressed by placement of sand to restore the beach and dune system.

(4). Behavior of artificial beaches and dunes. Artificial dune and/or beach restoration measures are simply replications of the comparable natural features and rely on the high wave-energy dissipation characteristics of such features as the means of protecting coastal developments. By comparison to other shore protection measures, restored beaches and dunes have the added advantage of possessing essentially the same aesthetic and environmental qualities as their natural counterparts. Artificial beaches and dunes are, in most cases, placed along shoreline reaches with a history of severe episodic and/or progressive long-term erosion. Because of this, the formulation and implementation of a beach/dune project requires a commitment to, and a plan for, a systematic sand replenishment, or anourishmenta program. Therefore, restored beaches and dunes are recurrent-cost intensive and should not be undertaken without the commitment and financial resources to perform replenishment operations as needed. Analyses of storm-tide/wave intensities and frequencies can usually establish reasonable values of expected return periods for these events and the associated beach/dune nourishment demands. The actual occurrences of the events, however, over periods of several years, may be either more or less frequent than the best analytical/statistical prediction of expected values would indicate. On balance, however, beach nourishment projects perform well throughout the world and are usually the method of choice in the protection of sandy shorelines.

(5). Construction of beach/dune projects. Beach and dune fills are most frequently constructed by hydraulic dredging methods. Borrow areas for projects are usually submerged sources of sediments and are normally located in estuaries, inlets or offshore areas. In this regard, there is increasing reliance on offshore sources to insure adequate long-term supply of material, to obtain appropriate sediment quality and to avoid destruction of valuable benthic organisms in estuaries. Material is conveyed to the beach and immediate nearshore zone by pipeline from the dredging site, while the onshore depositions are distributed and configured by earth-moving equipment into a typical beach/dune profile shape. The initial construction template over-builds the dry beach strand in order to provide sufficient material volume to be subsequently displaced, by wave action, to the submerged portions of the active beach profile. In relatively rare cases, the construction operation is done by using a land source of material, road haul and earth-moving equipment. Following material placement, an appropriate type of beachgrass usually stabilizes the dune feature. Sand fencing of various types can also be used for dune stabilization, but aesthetic value is lost by comparison to use of beach grasses. The objective is to reserve the dune(s) as a sacrificial defense line for major storm events. Dunes can be constructed quickly by direct placement of sand with hydraulic or mechanical means followed by stabilization by vegetation or sand-fences. Alternatively, dunes can be developed over longer time periods, through use of sand-fences and vegetation. When dunes have been developed by use of sand-fences, vegetation can be applied at the final stage to provide for a natural appearance plus added stability against the effects of wind.

3. Economic Principles.

a. Theory. The benefits of shore protection projects are difficult to measure. This difficulty was highlighted by the National Research Council in a 1995 report. The basic approach in developing the economic value of beach projects is to develop two scenarios for the proposed project area. The first scenario is awitha the project and the second is awithouta the project. The difference between these two projected streams of development is considered to represent the measure of the economic, social and environmental benefits and costs of the project. This procedure is a fundamental requirement of water resourcesa project planning as prescribed by the U.S. Water Resources Councils' aPrinciples and Guidelines.a

b. Project Formulation. Alternative plans are formulated in a systematic manner to ensure that all reasonable alternative solutions are evaluated. Usually, a number of alternative plans are identified early in the planning process and are refined in subsequent iterations. However, additional alternative plans may be introduced at any time. The Water Resources Development Act of 1986 (WRDA a86) specified that shore protection projects must be formulated for one purpose, to provide for storm damage reduction. Any enhancement of recreation that may also result is considered incidental. Such recreation benefits are National Economic Development (NED) benefits, however, and are included in the economic analysis. Additional beach fill, beyond that needed to achieve the storm damage reduction purpose, to better satisfy recreation demand would be a separable recreation feature which is not an Administration budgetary priority.

c. Types of Benefits. The major categories of allowed benefits for shore protection projects are storm damage reduction and erosion protection. Other benefit categories include recreation, reduced maintenance of existing structures, and enhancement of property values.

(1). Wave damage reduction benefits. In many areas, the most significant damages are caused by wave action. This category of damage can also be extremely difficult to accurately estimate particularly when damages are calculated on a structure-by-structure basis. Alternatively, an analyst familiar with the area may develop a matrix showing the percentage of the value of a particular structure type damaged by waves of a given magnitude.

(2). Inundation reduction benefits. Another significant benefit category is reduction of the inundation damages from coastal flooding. Inundation reduction benefits include the decrease of both physical and non-physical costs. These benefits include the saving of structures and contents from flood and salt-water damage, and the alleviation of clean-up costs, flood fighting expenses, evacuation costs, emergency aid, and traffic rerouting.

(3). Erosion reduction benefits. Structures are often more severely damaged by erosion of the land under them in coastal storms than from flooding. In some cases, they are totally destroyed. In other cases, where structures are elevated above flood levels, erosion can render them inaccessable and uninhabitable.

(4). Loss of land. The area of land that would be lost in the absence of the project over the period of evaluation may be estimated based on the historical rate of shore erosion in cases of long-term erosion. In instances of erosion due to coastal storms, the area that would be lost may be estimated with coastal erosion models that predict rates of erosion for storms of various frequencies.

(5). Recreation. Prior to the enactment of WRDA a86, projects were formulated for hurricane protection, beach erosion control, and recreation. For many projects, most of the benefits were associated with recreation. During the-mid 1980s, Army budgetary policy placed a lower priority on projects considered primarily recreation. This policy resulted in a shift to formulating projects for damage prevention, rather than for recreation. Following enactment of WRDA '86, Corps policy required that shore protection projects be formulated first for hurricane and storm damage reduction (HSDR). Additional beach fill beyond that required for the project formulated for HSDR, to satisfy recreation demand, is a separable recreation feature that is not supported for Federal participation under current budgetary policy. This policy is intended to focus Federal funds on the objective of reducing damages to coastal facilities. Recreation can still be used to partially justify projects. However, the extent to which recreation benefits can provide for economic justification is limited by current budgetary policy to 50 percent of benefits needed for project justification.

(6). Reduced maintenance of existing structures. Structures in the immediate vicinity of the shore may require more frequent maintenance because of recurring incidents of erosion. Benefits can be claimed to the extent that a project would reduce the extra maintenance. Reductions in the amount of beach nourishment required can also be claimed in this category.

(7). Enhancement of property values. Location and intensification benefits attributable to an erosion control project result from increased use of land through either intensified activities or by changing to an economically higher-valued development than would occur in the absence of the project. Such benefits result because of the higher utilization made feasible by increased safety of investments in improvements. Land enhancement benefits are over and above benefits received from damage reduction. These benefits apply only to land values and not to the value of future improvements.

d. Benefit Estimation Procedure.

(1). Storm damage reduction. The NED Procedures Manual for Coastal Storm Damage and Erosion recommends an eleven-step procedure for estimating storm damage reduction benefits. These eleven steps are: delineate the study area, define the problem, select planning shoreline reaches, establish frequency relationships, outline area affected, inventory existing conditions, determine most likely with- and without-project conditions, develop damage relationships, calculate damage-frequency relationships, compute expected average annual damages, and estimate total storm damage reduction and erosion prevention benefits.

(2). Recreation. Recreation benefits are those benefits derived from the availability of beach recreational area and the demand for use of that area by residents and tourists. Engineer Regulation 1105-2-100, Section VIII provides specific detailed procedures for evaluation of recreation benefits. In summary, an acceptable recreation evaluation has the following characteristics: the evaluation is based on an empirical estimate of demand applied to the particular project; estimates of demand reflect the socioeconomic characteristics of market area populations, recreation resources under study, and alternative existing recreation opportunities; the evaluation accounts for the value of loses or gains to existing sites in the study area affected by the project; and a willingness to pay is evaluated by (1) the travel cost method, (2) the contingency valuation method, or (3) by the unit day value method.

e. Estimation Reliability. Because of the great variability of storm, wind and wave activity in the coastal zone, potential damages are estimated by assuming that the past history of storm damage will repeat itself, in a statistical sense. Over a long period of time (disregarding climate change and sea level rise) this assumption is sound and the statistical distributions for storm and wave events should be very similar. For any specific period of 10, 20 or 50 years, however, this assumption may not hold. Hence, projects planned and designed today, on the basis of the previous 50 years of storm, wave and erosion data, may not be subject to the expected frequency of events over the next several years of performance.

4. Legislation and Policy.

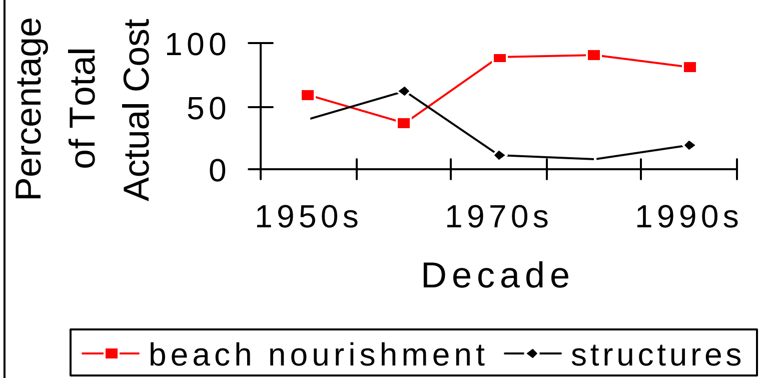
a. Authorizing Legislation. The legislative history of the Corps involvement in coastal activity is in direct correlation to the many storms the Atlantic and Gulf coastal states have been subjected to over the years. Because of the severe hurricane activity and the resulting death and destruction during the 1920's, Congress enacted Public Law 71-520. This 1930 law authorized the Corps to study (but not construct) shore protection measures in cooperation with state governments. Following World War II, the shoreline protection program of the Corps was expanded and consolidated through 22 additional legislative actions stretching from 1945 through 1999. A list of these 23 acts and a summary of each, are presented in **Appendix B**. The citations are limited to generic legislation and do not contain specific individual studies or project authorizations.

b. Historical Policy.

(1). Policy guidance. The Corps established policy guidance on shore protection can be found in Chapter 14 of EP 1165-2-1 *Digest of Water Resources Policies and Authorities,* (CECW-AG, dated 15 February 1996). A summary of the pertinent portions those policies plus the current Administrations proposals are provided in the following paragraphs.

(2). Background. Coastal shore protection projects have been constructed primarily in highly developed shoreline areas. Before World War II, the main approach to beach erosion and storm damage reduction was by using fixed structures, usually groins, jetties, and seawalls. In the late 1940's and early 1950's, an important change evolved in the basic concept of shoreline protection. Rather than relying solely on the traditional coastal structures of the past, it was realized that, in many situations, results would be more cost-efficient and functional if techniques were used which replicated the protective characteristics of natural beach and dune systems. This concept, pioneered in the early 1960's by the Corps, placed emphasis on the use of artificial beaches and dunes as economically efficient and highly effective energy dissipaters of wave energy (see **Figure 2-2**). Other important considerations were the environmental, aesthetic, and recreational values of artificially created beaches and the fact that beach nourishment projects also resulted in considerable benefits to adjacent shorelines.

Figure 2-2: Shift from Fixed Structure to Beach Nourishment



(3). Beach nourishment and renourishment. Initial restoration of a beach using artificially created beaches and dunes is not a permanent solution as ocean wave energies and littoral drift continue to cause losses to the project beach profile over time. Consequently, this type of project requires periodic nourishment or sand placement on the beach (which is considered continuation of construction) to be compatible with the economic life of structural solutions. Therefore, beach restoration projects include an estimate of initial beach restoration and an estimated frequency and quantity of periodic nourishment.

(4). Shift in policy. Historically, many shore protection projects were constructed for a combination of beach erosion control, storm damage prevention, and recreation purposes. A shift in Administration policy in the mid-1980's, precluded budgeting civil works funds for any additional (separable) beach area needed for recreation. This policy shift was supported in the 1986 Water Resources Development Act that identified new shore protection cost sharing only for hurricane and storm damage reduction projects. After that Act, policy guidance was issued requiring shore protection projects to be formulated for storm damage reduction alone and restricting any additional beach area or Federal costs for separable recreation.

(5). Privately owned shores. The Water Resources Development Act of 1986 also precluded Federal participation in projects that result in benefits to privately owned shores where the use of such shores is limited to private interests. Accordingly, policy guidance specifies that Federal hurricane and storm damage reduction projects must contain an item of local cooperation that assures the realization of public beach use throughout the economic life of the project, i.e., sufficient parking facilities for the public (including nonresident users) located nearby and reasonable public access to the project. The philosophy is that Federal civil works investments to protect private shorefront properties should allow accessibility to this natural resource by the public.

(6). Recreation. Existing policy guidance recognizes that recreation benefits realized because of the basic hurricane storm damage reduction project might exceed 50 percent of the total project benefits. However, economic justification must be proved based on recreation being limited to a maximum of 50 percent of that justification. This restriction prevents Federal participation in the construction of a project if its justification is primarily based on recreation benefits. However, even with this policy restriction on constructing primarily recreation projects, there is still a misperception that Federal beach nourishment projects are primarily for recreation and tourism purposes.

5. References.

National Research Council, "Beach Nourishment and Protection," National Academy Press, 1995.

National Resources Council's "Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies, March 1983.

U.S. Army Coastal Engineering Research Center, "Shore Protection Manual Vols. I and II)," 1984.

U.S. Army Corps of Engineers, "EM 1110-2-3301, Engineering Design of Beach Fills," June 1994.

U.S. Army Corps of Engineers, "EP 1165-2-1, Digest of Water Resources Policies and Authorities," February 1996.

U.S. Army Corps of Engineers, "ER 1105-2-100, Planning and Policy Guidance," December 1990.

U.S. Army Corps of Engineers Institute for Water Resources, "National Economic Development Procedures Manual, Coastal Storm Damage and Erosion," IWR Report 91-R-6, September 1991.

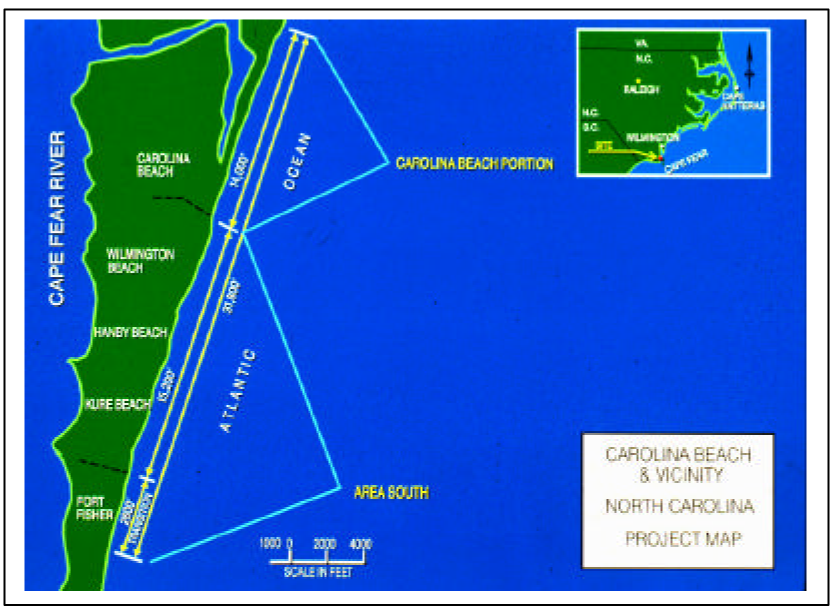
U.S. Army Corps of Engineers Institute for Water Resources, "Shoreline Protection and Beach Erosion Control Study," IWR Report 96-PS-1, June 1996.

B. KURE BEACH

1. Location. The Kure Beach project is in New Hanover County, about 15 miles south-southeast of Wilmington, North Carolina, see Figure 2-1. The area covered by the project consists of about 3.4 miles of the North Carolina ocean shore along the peninsula that separates the lower Cape Fear River from the Atlantic Ocean. The project is bordered on the north by the Carolina Beach project and on the south by Fort Fisher.

2. Authorization. The Area South of Carolina Beach project (Kure Beach) was authorized by Congress in 1962 (House Document Number 418, 87th Congress, 2nd Session) as part of the Carolina Beach and Vicinity Project. The project, as originally authorized, consisted of a 25,800-foot long project divided into two sections; the Carolina Beach project and the Area South of Carolina Beach (**Figure 2-3**). The Area South of Carolina Beach portion of the authorized project called for the protection of 13,050 feet of shoreline which included two unincorporated areas (Wilmington Beach and Hanby Beach) and one incorporated area, Kure Beach. A design memorandum for the Area South portion was prepared in 1967. Local sponsors, however, did not support the project and in 1974 the project was placed in the inactive category. Following severe damage to coastal development and beaches caused by Hurricane David in September 1979 and Hurricane Diana in September 1984, local sponsors indicated a renewed interest in the project and it was reclassified as active in 1985. An economic reevaluation of the Area South project was completed in 1989, demonstrating a favorable benefit-to-cost ratio. The Town of Kure Beach agreed to be the non- Federal sponsor for the entire Area South project.

Figure 2-3; Carolina Beach and Vicinity Project



3. Project History.

a. Project Description. Following the favorable finding by the economic reevaluation, a Design Memorandum Supplement (DMS) was prepared. This DMS analyzed the shoreline conditions and the available borrow material, thereby formulating a National Economic Development (NED) plan, which identified the plan that provides the maximum net benefits. The DMS was completed in January 1993. The NED plan consisted of a 25-foot wide dune with a crest elevation of 13.5 feet NGVD and fronted by a 50-foot wide berm at an elevation of 9.0 feet NGVD. The total project length was expanded to 18,000 feet in order to cover areas incorporated into Kure Beach since project authorization. Included in the 18,000-foot total project length is a 1,500-foot transition at the south end. The northern terminus of the project adjoins the Carolina Beach portion of the authorized project. The southern terminus of the project ends approximately 1,000 feet north of the end of the developed portion of the beach. This terminal point of the project was primarily dictated by the existence of a natural coquina rock outcrop, which was judged to be environmentally important and should not be covered. Secondary reasons for terminating the project at this point were related to concerns over accelerated losses of material from the end of the project due to an abrupt change in shoreline orientation that occurs at the north boundary of the Fort Fisher State Historic Site. The abrupt change in shoreline orientation would have necessitated the use of a terminal groin at the south end of the project to limit losses from the fill. North Carolina coastal regulations prohibit the use of hard structures and would, therefore, not have been permitted.

b. Planned Project Design. The estimated volume of material required to initially construct the Area South project and to provide three years of advanced nourishment totaled 3,372,000 cubic yards. Periodic nourishment is to be accomplished at three-year intervals with an estimated renourishment volume of 766,000 cubic yards. The performance of the Carolina Beach portion of the project was used as a aprototype modela in estimating the nourishment requirements for the Area South project. Borrow areas for the construction and periodic nourishment of the project are located offshore in water depths ranging from 35 to 45 feet below NGVD. Two main borrow areas were located for the Area South project. The southernmost area was to be used for initial construction and the first two to three nourishment cycles. Once this source is depleted, the nourishment material would be obtained from the northern borrow area. The borrow areas are paleo-channels of the Cape Fear River, estimated to be at least 25 million years old.

c. Initial Construction. A contract for the construction of the Area South project was awarded in August 1996. Before the contractor could mobilize to the area, Hurricane Fran hit the area and caused considerable damage to the beaches and development within the limits of the project. Due to damages caused by the storm, the beach was resurveyed and revised plans and fill quantities determined. Work on the project did not begin until the spring of 1997. Previous environmental coordination on the project had resulted in a one-time agreement with the various resource agencies to allow construction of the project to continue through the summer months to take advantage of the milder wave conditions. Placement of the fill along the project shoreline was completed in February 1998. The final fill volume of about 3.4 million yards was very close to the estimate. Work on other elements of the project, such as storm water outfalls, dune walkover structures, and dune vegetation continued for several months following the completion of the fill. The final cost of the project has not yet been determined, but the cost is estimated at approximately $15.0 million (see **Table 2-1**). The final estimated cost of about $15 million equates to about $4.4 million per mile of beach. Photographs of the project area before and after placement of the fill are shown, respectively, on **Photos 2-1, 2-2.**

Table 2-1: Kure Beach Project Cost

Item	Cost ($)
Initial Fill (3,384,854 cubic yards)	$ 9,293,200
Storm drain modifications, extension and/or replacement of public walkover structures, and grassing of the artificial dunes.	1,783,981
Replanting and refertilization of the dune grass and final modifications in the walkover structures and drains.	Unknown
Planning, engineering and design, which include costs for the economic reevaluation and supplement to the design memorandum (approximately).	2,300,000
Credit to the local sponsor for cost incurred in obtaining the necessary easements for project construction.	Unknown
Total estimated cost (approximately)	**15,000,000**

Photo 2-1: Kure Beach before Fill Placement

Photo 2-2: Kure Beach after Fill Placement

C. CAROLINA BEACH

1. Overview. The Carolina Beach project is in New Hanover County, about 15 miles south southeast of Wilmington, North Carolina, see Figure 2-1. The area covered by the project consists of about 2.6 miles of the North Carolina Ocean shoreline along the peninsula that separates the Lower Cape Fear River from the Atlantic Ocean. The project is bordered on the north by Carolina Beach Inlet and on the south by Kure Beach, see **Photo 2-3**. This particular photo was taken during one of the recent renourishment operations. The tidal inlet at the top of the photo is Carolina Beach Inlet. A sediment trap in the throat of the inlet serves as a renewable source of sand for the periodic nourishment operations. The north end of the project is near the fishing pier located at the north end of the developed section of the beach. The portion of the project lying north of the point where the dune vegetation ceases to the fishing pier is protected along the oceanfront by a rubble mound revetment. The discharge end of the dredge pipe is just north of the main business area of Carolina Beach know as the Boardwalk.

2. Authorization. The Carolina Beach project was authorized by Congress in 1962 (House Document Number 418, 87th Congress, 2nd Session) as part of the Carolina Beach and Vicinity Project. The project, as originally authorized, consisted of a 25,800-foot long project divided into

Photo 2-3; Carolina Beach Project during a Recent Nourishment Operation

two sections, the Carolina Beach project and the Area South of Carolina Beach. The Carolina Beach portion of the authorized project called for the protection of 12,750 feet of shoreline lying totally within the town limits of Carolina Beach. This portion of the project called for a beach fill shaped to form a 25-foot wide dune with a crest elevation of 13.5 feet above NGVD fronted by a 50-foot wide storm berm at elevation 10.5 feet above NGVD. The Carolina Beach project was later modified to include a 2,050-foot long rock revetment at the extreme north end of the project that is fronted by a 130-foot wide berm at elevation 6.5 feet above NGVD. In 1993, the Carolina Beach project was reevaluated under the authority of Section 934 of the Water Resources Development Act of 1986 (PL 99-662). Under this study, the project was found to be eligible for continued Federal participation in beach nourishment, for a period of 50-years from initiation of construction. Since construction was initiated in 1964, Federal cost sharing in beach nourishment will continue through the year 2014.

3. Project History.

a. Initial Construction. The initial stage of construction for the project was completed in April 1965 with the placement of 2,632,000 cubic yards of borrow material obtained from the Carolina Beach Harbor area. Immediately following the initial placement, severe erosion occurred along the entire length of the fill.

(1). Southern portion. Over the southern 10,000 feet of the project, the erosion was attributed to hydraulic sorting of the borrow material by waves and the movement of the borrow material down slope to deeper portions of the active beach profile. These initial sorting and slope adjustments continued until 1967 at which time this southern portion became fairly stable. By the time stability was reached, however, the cross section of the fill was somewhat less than the authorized section.

(2). Northern portion. The erosion that occurred along the northern 4,000 feet of the project was considerably greater than that which could be explained by hydraulic sorting and slope adjustment. Within the first year following the initial fill placement, essentially all of the fill material was eroded. Authority was therefore granted to proceed with emergency measures involving the placement of 411,000 cubic yards of fill and the construction of a temporary timber groin at the northern end of the project. These emergency corrective measures were completed in March 1967. The emergency fill was completely gone within a year and the temporary groin was undergoing rapid deterioration. The continuation of the severe erosion necessitated additional emergency action involving the construction of a 2,050-foot long rock revetment extending southward from the north terminus of the project and the placement of 346,000 cubic yards of fill. The revetment was constructed in two stages with the first stage along with the placement of the fill completed in December 1970. The second stage revetment was completed in September 1973.

b. Special Study. During the mid-1960's, when the inordinate erosion was occurring along the northern end of the project, a special investigation of the problem was authorized to determine the causes and to recommend a feasible long-term solution. This special investigation was completed in 1970. This special study and a subsequent study of the feasibility of improving navigation through Carolina Beach Inlet identified the entrapment of littoral material in the inlet as the cause of the erosion problem. The long-term solution recommended in the subsequent Carolina Beach Inlet report involved the bypassing of littoral sediment every three years from a sediment trap located in the throat of the inlet. This sand would be distributed along the north end of the project and would serve as a source of sediment for the beach to the south. Both reports concluded that the failure to accomplish the sand bypassing on a regular basis would result in the continued deterioration of the entire project, as the severe erosion associated with the inlet deficit would migrate southward.

c. Project Completion.

(1). 1971- 1980. In early 1971, 760,000 cubic yards of fill were placed along the entire length of the project to restore the project to its authorized dimensions. For the decade following this nourishment, no additional fill material was placed on the project shoreline. As a result, the severe erosion migrated to the south, as predicted, leaving only the southernmost 2,000 feet of the project showing any degree of stability.

(2). Emergency fill. In December 1980, the southeastern coastal area of North Carolina was struck by two severe northeasters that further aggravated the erosion at Carolina Beach, particularly along the section of the project located just south of the rock revetment. In this area, seven cottages were undermined and were condemned. Further south, the shoreline had moved to within 25 feet of 122 other structures, making them vulnerable to damage in the event of another moderate storm. In response to the cumulative effects of the inlet related and storm induced shoreline retreats, 406,000 cubic yards of emergency fill were placed between stations 60+00 and 120+00 during April and May 1981. This emergency fill was only intended to partially rebuild the severely eroded section of the project in order to provide protection against moderate storms until the entire project could be restored to authorized dimensions.

(3). Sediment trap. The material for the emergency fill was obtained from a borrow area located in Carolina Beach Inlet. This borrow area began at the Atlantic Intracoastal Waterway and extended approximately 2,000 feet seaward. The removal of the material for this section of the inlet effectively created a sediment trap that could supply material for future beach nourishment operations in accordance with the long-term erosion control plan for Carolina Beach.

4). Final project. Construction of the Carolina Beach project was completed in July 1982 following the placement of 3,662,000 cubic yards of sand along the entire length of the project. This final phase of construction completely restored the berm and dune section up to the southern end of the rock revetment and provided a 130-foot wide berm at elevation 6.5 feet NGVD in front of the revetment. As part of the 1982 renourishment, a substantial construction berm was placed in front of the authorized cross section at an elevation of 6.5 feet NGVD. Construction berms are designed as a sacrificial material source, which contain the volume of material necessary to nourish the deeper portions of the active beach profile. The Carolina Beach project has performed well since 1982 with periodic nourishment being accomplished approximately ever 3 years. The nourishment and cost history of the project is shown in **Table 2-2**.

Table 2-2: Carolina Beach Summary of Nourishment Operations

Dates		Type of Fill	Coverage (baseline stations)	Cubic Yards Placed [1]	Cost ($) [2]
12/15/64	5/18/65	Initial	0+00 to 140+00	3,579,362	$ 925,506
3/1/67	6/30/67	Renourish	100+00 to 140+00	389,959	186,308
4/13/70	6/5/70	Emergency	60+00 to 120+00	282,423	291,159
12/11/70	5/31/71	Renourish	0+00 to 140+00	734,140	788,005
4/27/81	5/27/81	Emergency	60+00 to 120+00	406,352	1,051,774
12/28/81	8/12/82	Renourish	0+00 to 140+00	3,662,181	8,384,406
4/19/85	6/4/85	Renourish	80+00 to 140+00	764,162	1,652,004
3/16/88	4/27/88	Renourish	85+00 to 142+00	950,913	1,890,535
5/11/91	7/1/91	Renourish	0+00 to 140+00	1,008,736	2,450,286
2/95	5/95	Renourish	0+00 to 140+00	1,157,742	3,185,642
	1998	Renourish	0+00 to 140+00	1,204,646	2,894,060
Totals				**14,158,616**	**$23,699,685**

Footnotes:
[1]. It is estimated that 4,073,228 cubic yards can be attributed to sorting losses. Net fill, therefore, is 10,085,388 cubic yards.

[2]. The unit cost of material placement has been between a low of $0.257 for the initial fill in 1964-1965, to a high of $2.752 for the 1995 renourishment. The average cost of fill placement has been almost $1.674 per cubic yard.

D. WRIGHTSVILLE BEACH

1. Overview. The area covered by the Wrightsville Beach project is a small island off the coast of North Carolina, about 10 miles east of Wilmington (see Figure 2-1) in New Hanover County. It is separated from other portions of the barrier beach by Masons Inlet on the north and by Masonboro Inlet on the south. The island is separated from the mainland by a sound that consists of open channels, salt

marsh, a small island (Harbor Island), and the Atlantic Intracoastal Waterway (see **Photo 2-4**). Masonboro Inlet is in the upper left-hand portion of the photo. The large high-rise structure in the lower mid-portion of the photo is the Islander Condominium This building is located at the north boundary of the Federal storm damage reduction project. Johnnie Mercer's fishing pier is located in the middle of the photo. The shoreline segment north of the Islander Condominium is

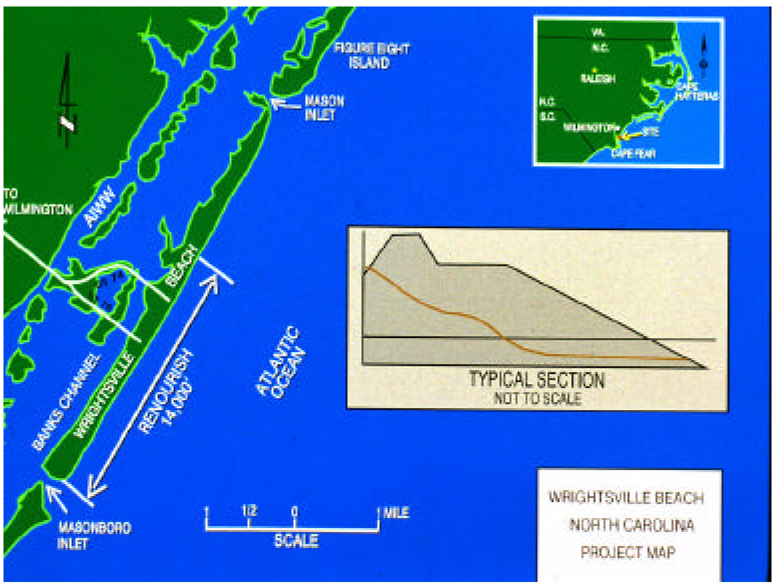
Photo 2-4: Wrightsville Beach Project

know as Shell Island. Shell Island was incorporated into Wrightsville Beach in the min-1980's. Consideration was given to possibly extending the Federal storm damage reduction project to Shell Island. However, the condition of the beach in this area, which consists of a large dune and wide high tide dry beach, rendered additional protection unnecessary. The large dune and wide beach are by-products of the Wrightsville Beach project. Material from this project is transported north during sediment transport reversals. The natural tendency of the shoreline bulge created by the nourishment to be flattened by waves and the accompanying littoral sediment transport pattern, also helps in maintaining a natural beach.

2. Authorization. The Wrightsville Beach project was originally authorized in the Flood Control Act of 1962 (Public Law 87-874). The project covers 14,000 feet of ocean shoreline extending north from Masonboro Inlet (see **Figure 2-4**). The project consists of a beach fill shaped in the form of a 25-foot wide dune at elevation 13.5 feet above NGVD fronted by a 50-foot wide storm berm at elevation 10.5 feet above NGVD. A reevaluation of the project was made in September 1982 with the results

provided in a report entitled aFeasibility Report and Environmental Assessment on Shore and Hurricane Wave Protection, Wrightsville Beach, North Carolina." As a result of this reevaluation, the Wrightsville Beach project was reauthorized by the Water Resources Development Act of 1986 (Public Law 99-662). The new authorization extended the Federal cost sharing for beach nourishment for a period of 50-years from initiation of construction.

Figure 2-4; Wrightsville Beach Project Map



3. Project History.

a. 1965. The initial construction of the Wrightsville Beach project was accomplished in 1965 with the placement of 2,993,100 cubic yards of material, north from Masonboro Inlet, along 14,000 lineal feet of shoreline. Included in the initial construction was the closure of a small tidal inlet at the northern end of the project. This inlet was known as Moore Inlet and separated the town of Wrightsville Beach from Shell Island. Material to initially construct the project was obtained from Banks Channel, a narrow sound lying immediately behind Wrightsville Beach. This initial borrow material was not entirely suited for beach fill; consequently, the fill experienced some initial sorting and winnowing losses. In addition, large quantities of the fill material were moved downslope to deeper portions of the active beach profile. The erosion of the upper portion of the fill that occurred with this offshore movement was primarily due to the failure to place a sufficient quantity of sand to nourish the entire active profile. At Wrightsville Beach, the active profile extends to a depth of 20 to 25 feet below NGVD whereas design slopes assumed for the fill closed in depths of 6 to 10 feet NGVD.

b. 1966. Construction of the north jetty at Masonboro Inlet began immediately following the initial placement of the Wrightsville Beach fill. Associated with the construction of the north jetty was the excavation of a sediment trap adjacent to the weir section of the jetty. The material removed to construct the deposition basin, which totaled about 319,000 cubic yards, was placed on Wrightsville Beach between 3,000 feet and 13,000 feet north of the inlet. Construction of the sediment trap occurred between March and July 1966 or about one year after initial construction of the beach project.

c. 1970. No additional fill was placed on Wrightsville Beach until 1970, at which time about 1.4 million cubic yards was placed along the northern 8,000 feet of the project to correct the earlier design deficiency and replace material lost to sorting and winnowing. The material for this operation was obtained from the southern end of Banks Channel near Masonboro Inlet and from the sound behind Shell Island. The southern 6,000 feet of the project has not required any nourishment since initial construction as it lies within the accretion fillet of the Masonboro Inlet north jetty.

d. 1980. In April 1980, approximately 541,000 cubic yards of sand obtained from the southern end of Banks Channel was placed along the northern 8,000 feet of the project to replace sand lost as a result of Hurricane David which passed near the area in September 1979. The post-Hurricane David fill did not completely restore the design cross section in the north portion of the project. This northern portion was completely restored between December 1980 and April 1981 with the placement of 1,250,000 cubic yards of material obtained from Masonboro Inlet in connection with the restoration of the inlet bar channel between the north jetty and the recently completed south jetty. Adjustments continued until 1967 at which time this southern portion became fairly stable. By the time stability was reached, however, the cross section of the fill was somewhat less than the authorized section.

e. 1986. Following the 1981 restoration of the project, serious erosion problems persisted, particularly along the northern portion of the project. Studies of this erosion problem attributed 46 percent of the erosion on Wrightsville Beach to the Masonboro Inlet navigation project and the remaining 54 percent to other non-inlet-related causes. The primary non-inlet related factor contributing to the erosion is the convex seaward planform of the island created with the closure of Moore Inlet. The Masonboro Inlet project was also creating a sediment deficit on Masonboro Island, the undeveloped barrier island lying south of the inlet. In 1986, the first official sand bypassing operation was carried out at Masonboro Inlet when 900,000 cubic yards of sand was placed on Wrightsville Beach and 1,250,000 cubic yards place on Masonboro Island. Since 1986, sand bypassing from the inlet and renourishment of the Wrightsville Beach project has been accomplished jointly approximately every four years.

f. Summary Tables. The nourishment and cost history of the Wrightsville Beach project are shown in **Table 2-3**.

Table 2-3: Wrightsville Beach Summary of Nourishment Operations

Dates		Type of Fill	Source of Material	Cu. Yds. Placed [1]	Cost ($) [2]
2/18/65	7/30/65	Initial	Banks Channel	2,993,100	$ 739,339
3/23/66	7/7/66	Deposition Basin	Masonboro Inlet	319,408	247,493
10/8/66	10/12/66	Nourishment	Behind Shell Island	42,700	8,448
3/16/70	5/22/70	PL 99, O&M, CG	S. End Banks Ch.	1,436,533	578,545
3/31/80	5/22/80	PL 99	S. End Banks Ch.	540,715	1,030,736
12/6/80	4/11/81	PL 99,O&M, CG, Sec 111	Masonboro Inlet	1,249,699	4,427,792
4/10/86	6/86	Sand Bypassing	Masonboro Inlet	898,593	1,331,715
1/31/91	5/22/91	Scheduled Nourishment and Bypassing	Masonboro Inlet	1,016,684	2,682,412
4/22/94	5/19/94	Scheduled Nourishment and Bypassing	Masonboro Inlet	619,031	1,973,591
	1998	Scheduled Nourishment and Bypassing	Masonboro Inlet	1,116,573	2,640,292
Totals				**10,233,036**	**$15,660,363**

Footnotes:
[1]. It is estimated that a total of 1,606,000 cubic yards can be attributed to sorting losses. Net fill is, therefore, 8,627,036 cubic yards.

[2]. The unit cost of fill placement has been between a low of $0.198/cy in October 1966 to a high of $3.543 in the December 1980 to April 1981 placement. The average cost of fill placement has been $1.53/cy.

E. TOPSAIL ISLAND

1. Location and History. Topsail Island is a barrier island on the central North Carolina coast in Pender and Onslow Counties. The island is about 22 miles long and stretches from New Topsail Inlet on the south to New River Inlet on the North. The southern limit of the island is about 20 miles northeast of Wilmington, NC (see Figure 2-1). Before 1941, Topsail Island, then called aAshe Island,a was a stock-grazing range with no development or access to the mainland other than by boat. In 1941 the island was acquired by the U.S. Government and was used as a military reservation until 1947. A paved access road from the mainland, a drawbridge over the Intracoastal Waterway and a paved road the length of the island were constructed by the military during the time of its occupation. After 1947, the island was returned to private

ownership and since about 1950, has been extensively developed by private interests as a year-round residential area and a summer resort. The island consists of three communities: Topsail Beach, which extends along the southern portion of the island for a reach of about 4.5 miles, Surf City, which covers the 6.2 mile central portion, and North Topsail Beach that comprises the northern 12 mile section.

2. Study.

a. Authority. The Corps of Engineers completed a study of this area in 1989. This study was conducted pursuant to three Congressional Resolutions: 24 June 1970, 23 June 1971 and 14 November l979. The first study authority was directed to the navigation needs of New River Inlet and the latter two were in the a . . . interest of beach erosion control, hurricane protection, and related purposes.a The 1971 Resolution was for West Onslow Beach (now North Topsail Beach) and the areas of Topsail Beach and Surf City were covered by the 1979 Resolution.

b. Topsail Beach. Topsail Beach has developed as a family-based ocean resort community for outdoor recreation. Except for some dune areas, the entire town is subject to hurricane flooding. The 1989 study found that along the southern 2 miles of Topsail Beach erosion was progressing at an average rate of about 4.5 feet per year and that the natural protective dune was nonexistent. Several structures had been lost to erosion or relocated. At that time, the area most threatened by erosion and hurricane overwash was thought to be near three canals on the south end of the island. Private interests in the 1970's excavated these canals. At its narrowest point, opposite these canals, the island had a width of only 200 feet. During the 1990's, however, erosion has stopped and this part of the island is accreting.

c. Surf City. Like Topsail Beach, Surf City is a heavily developed resort community (see **Photo 2-5**). This development is also subject to flooding during severe storms and land losses due to beach erosion have occurred. At the time of the 1989 study, however, the shoreline at Surf City was considered generally stable, and had a natural dune system.

d. North Topsail Beach. As with Topsail Beach and Surf City, North Topsail Beach (formerly known as West Onslow Beach) is in a flood prone area. The only road along the northern half or the beach is just landward of the foredunes and is vulnerable to storm overwash and erosion. During Hurricane Hugo in 1989, a 2,000-foot-long segment of this road was lost. An obvious beach erosion and hurricane damage potential exists along the entire beach. However, the 1989 study found that damage potential in this area was not sufficient to justify detailed consideration of Federal shore protection and beach erosion control measures. In addition, the major part of the beach is included within the "Coastal Barrier Resources System." This system, authorized by Public Law 97-348, limits Federal expenditures for studies, and projects within this system.

Photo 2-5; Surf City

e. Recommendations. While potential for hurricane damages and beach erosion exists at Surf City and North Topsail Beach, Federal improvements at these communities were found not practical during the 1989 study due to economic and environmental constraints. The only area of Topsail Island where a Federal project was determined to be economically feasible and environmentally acceptable was the southern 3-mile portion of the island in Topsail Beach.

3. Topsail Beach.

a. Pre-authorization Planning. During project planning, two options surfaced, one with a terminal groin and one without. The terminal groin would have been positioned just north of New Topsail Inlet (at the south end of the project) and would have reduced periodic nourishment by approximately one-half (once four years instead of once ever two years). As a result of the lesser nourishment cost, the annual cost of the terminal groin plan was considerable less than the plan without the terminal groin. Because of this lesser cost (the benefits of the two plans were the same), the terminal groin plan was designated the National Economic Development (NED) plan and was used to establish the limit of Federal cost sharing for the project. Under the NED plan, the Federal share of costs is set at 65 percent for both initial construction and periodic nourishment. Policies of the State of North Carolina, however, prohibit the use of hard structures to control erosion along the ocean shoreline of the State and further consideration of the terminal groin plan was discontinued.

b. Authorized Project. The Topsail Beach project was subsequently authorized by the Water Resources Development Act of 1992. The authorized project, described in House Document 102-393, consisted of a 18,760-foot beach fill along the southernmost portions of the Town of Topsail Beach. The beach fill was composed of a main fill, which measured 9,500 feet in length bordered on the north by a 6,860-foot transition section and on the south by a 2,400-foot transition section. The cross-sectional configuration of the main fill consisted of a 25-foot wide dune at elevation 13 feet above National Geodetic Vertical Datum (NGVD) fronted by a 35-foot wide storm berm at elevation 9.0 feet NGVD which was in turn fronted by a 40-foot wide natural berm at elevation 7.0 feet NGVD. This configuration of the main fill would have moved the shoreline an average of 160 feet seaward. The north and south transitions had variable width natural berms at elevation 7.0 feet NGVD. Periodic nourishment for the project would be required every two years.

c. Cost Sharing Determination. The plan described above (the plan without the terminal groin), even though annual costs were higher, was the one supported by the State of North Carolina. Since the State of North Carolina is normally a major cost sharer for Federal coastal protection projects (State law allows the State to pay up to 75 percent of the non-Federal share) it was designated as the Locally Preferred Plan (LPP). As a result of the lower average annual cost for the plan with the terminal groin, the non-Federal cost share for the LPP plan was increased from 35 percent to 46 percent. Not only was the non-Federal share increased, but the average annual cost for nourishing the project every two years versus every four years with the NED plan resulted in the non-Federal sponsors having to assume responsibility for a larger percentage of a much higher annual cost.

d. Support Withdrawn. During project planning the Town of Topsail Beach made several attempts to obtain approval for the terminal groin plan from North Carolina Coastal Resources Commission (the State commission that oversees the coastal management program), but to no avail. Simultaneously, a design memorandum for the Topsail Beach project was completed in August 1992 and work on the plans and specifications initiated. However, the Town of Topsail Beach notified the Corps of Engineers that it would not be able to financially support the project (even with State help) due to the projected high nourishment cost and the at the high rate of non-Federal cost sharing. As a result, the project was placed in the inactive category.

CHAPTER 3
PHYSICAL SETTING

A. WINDS

1. Setting the Stage. This component of the study pertains to an evaluation of onshore winds near the North Carolina coast during Hurricanes Bertha and Fran and attempts to address the question of whether the Wilmington area beaches (Kure, Carolina, Wrightsville, and Topsail Island) (see Chapter 2, Figure 2-1) had significant differences in winds. To address these questions, various sources of information (Internet, National Hurricane Center, National Climatic Data Center, and Air Force) were accessed. From these sources, wind data were gathered, hand edited, and plotted. A number of onshore wind sites exist within a 100-mile radius of Wilmington, which have gathered a variety of wind information. Data recording was sporadic during most of the periods of interest (i.e., two days before landfall and one day after landfall of the storms). In many cases the data is of limited use due to equipment malfunctions during the wind extremes of the storms. Additionally, due to the gradients of the wind in the storms, only records reasonably close to the beaches were used. Because of the dramatic reduction of wind when the storms came ashore (i.e., friction effects), only three primary onshore sites (Myrtle Beach, SC; Wilmington, NC and New River, NC) were utilized in drawing conclusions for this limited onshore wind study.

2. Onshore Stations. Provided as **Appendix C, Pages C-2 -10** are plots of 10 minute average wind speeds (knots) (1 knot equals 1.15 miles per hour), the maximum wind speed (knots) in 10 minute intervals (i.e., gusts), and wind direction (degrees) at the three primary onshore sites, Myrtle Beach, Wilmington and New River. New River is just north of North Topsail Island. Additional plots at Cherry Point, NC, are also provided but are not discussed further. Given in **Table 3A-1** for the three primary stations are the results of sustained wind speed and gusts. An example of the actual reading for the Wilmington, NC station is provided as **Appendix C, Pages C-11 -31**. This example has been hand edited for missing data.

Table 3A-1: Winds at Onshore Stations

Location	Storm	Sustained Wind Speed (knots)	Gust (knots)
Myrtle Beach, SC	Bertha	27	40
	Fran	35	46
Wilmington, NC	Bertha	43	59
	Fran	51	75
New River, NC	Bertha	45	>48
	Fran	50	70

3. Offshore Towers. Additional wind speed data exist at offshore towers in the nearshore zone. Although a number of these offshore stations exist within the South Carolina and North Carolina coastal zone, only two are in the near vicinity of the beaches in question. These stations are Frying Pan Shoals, NC and Cape Lookout, NC. Plots of the maximum wind speed, gusts and directions are provided in **Appendix C, Pages C-32 -35**. Over water aoffshorea winds at these stations in provided in **Table 3A-2**. The reasons for higher winds at these offshore locations are threefold:

- The recording height is higher than the 10-meter standard height at the onshore locations, i.e.; the anemometer is at 44.2 meters (above mean sea level) height for Prying Pan Shoals and 14.4 meters (above means sea level) for Cape Lookout.
- The wind speed is recorded over water where frictional effects are less and hence wind speeds are higher.
- Wind speed was reported for time averaging over a shorter time interval (two minutes).

Table 3A-2: Winds at Offshore Towers

Location	Storm	Sustained Wind Speed (knots)	Gust (knots)
Frying Pan Shoals – approximately 50 miles south of Wilmington	Bertha	72	87
	Fran	79	94
Cape Lookout – approximately 75 miles northeast of Wilmington, and approximately 45 northeast of North Topsail Beach.	Bertha	53	62
	Fran	56	67

4, Data Checks.

a. New River and Cape Lookout, NC. Additional work was provided on two sites: one onshore (New River, NC) and one offshore tower (Cape Lookout, NC). The near vicinity of these gages allowed the comparison of wind speeds to provide an aapproximatea reduction factor to account for the last two items described in above paragraph A3. As the wind gages were at approximately the same height above mean sea level, no correction for elevation appears necessary. A scatter plot of the asustaineda wind speeds at the two locations is provided as **Appendix C, Page C-36- 37**. Regression analysis on values (with zero values and a minimal number of outliers filtered out) provided an adjustment factor of (0.6) to be applied to the Frying Pan Shoals data to acrudelya adjust the Frying Pan shoals data to the land-based stations (i.e., accounting for the factors of the last two items in above paragraph A3. Multiplying the Frying Pan Shoal asustaineda wind speeds by the 0.6 adjustment factor provides values reasonably close to the observed values obtained at the New River and Wilmington land-based stations. As the Frying Pan Shoals data should be reduced further due to the elevation above standard anemometer (10 meter) height, the data suggests that the aonshorea winds were somewhat higher North of Kure Beach.

b. Other Sources.

(1). Additional unverified wind speeds were noted in various sources (i.e., newspaper articles, National Weather Service preliminary storm reports, non-WMO standard stations, etc.). Such unverified wind speeds consist of possibly nonstandard wind recording instruments that have not been properly calibrated, nonstandard recording height, and unknown or uncertain time averaging wind period. Attempts to obtain wind speed records from non-WMO standard wind gages at Cherry Grove Pier, SC; Kure Beach, NC; Figure Eight Island, NC; and North Topsail Beach, NC were made but data had not been received at the time of report writing and limited funding would not have allowed the analysis of these gages. The only unverified wind speed data available for comparison was for Hurricane Bertha. This data showed sustained wind speeds of 49 knots at Kure Beach and 65 knots at Topsail Beach.

(2). None of the numerous news articles scanned on either Bertha or Fran suggested any appreciable atornadica activity along these stretches of beach. Localized differences in wind patterns above and beyond these ageneral a patterns may have occurred but insufficient wind measurements exist to define such differences adequately.

(3). Based on information from the National Hurricane Center (NHC), Bertha winds were at 90 knots (estimated maximum 1-minute wind speed at landfall) when, on the 12th of July, the center crossed the coast of North Carolina midway between Wrightsville Beach and Topsail Island. The NHC reported that Bertha quickly dropped below hurricane strength when it moved inland over eastern North Carolina. The NHC reported that the center of Fran moved over the Cape Fear area on the 6th of September, but the circulation and radius of maximum winds were large and hurricane force winds likely extended over much of the North Carolina coastal areas of Brunswick, New Hanover, Pender, Onslow and Carteret counties. At landfall, the maximum sustained surface winds are estimated at 100 knots. The strongest winds likely occurred in streaks within the deep convective areas north and northeast of the center. Fran weakened to a tropical storm while centered over central North Carolina and subsequently to a tropical depression while moving through Virginia.

(4). Preliminary work by the NHC, indicate the wind speeds from the two storms are generally similar over the beach areas with higher wind speeds existing over the northernmost beaches due to the wind gradient pattern of the storm. A map produced by the Nation Research Division of NOAA, which analyzed surface winds at one instant during Hurricane Fran is provided as **Appendix C, Page C-38**.

5. Conclusions. Based on all the best available wind speed data, the overall onshore wind speed patterns were not significantly different for the beaches in question although, for Hurricane Fran, slightly higher winds were recorded in the Kure – Carolina – Wrightsville area as compared to Topsail Island.

B. STORM SURGE

1. Introduction. The purpose of this investigation is to evaluate relative severity of storm surge elevation impact of Hurricanes Fran and Bertha on the open coast of North Carolina. Specifically, impacts to the areas including Topsail, Carolina and Kure Beaches are examined. This investigation requires specification of topography and bathymetry in the study area, modeling of the wind and pressure fields associated with Hurricanes Fran and Bertha, and the numerical modeling of the storm surge associated with each event. Results of the study are presented as maximum water surface elevations at three sites and as a spatial distribution of maximum water level distribution along the coast. The following paragraphs describe the surge model and associated computational grid, the hurricane model, and modeling results.

2. Storm Surge Model.

a. General. The storm surge model used in this study is the ADvanced CIRCulation (ADCIRC) hydrodynamic model. The ADCIRC model is an unstructured grid finite element long-wave hydrodynamic model, which was developed under the 6-year CE-funded Dredging Research Program (DRP). The model was developed as a family of 2- and 3-Dimensional codes (Luettich et al., 1992; Westerink et al., 1992) with the capability of:

(1). Simulating tidal circulation and storm surge propagation over very large computational domains while simultaneously providing high resolution in areas of complex shoreline and bathymetry. The targeted areas of interest included continental shelves, nearshore areas, and estuaries.

(2). Properly representing all pertinent physics of the 3-dimensional equations of motion. These include tidal potential, Coriolis, and all nonlinear terms of the governing equations.

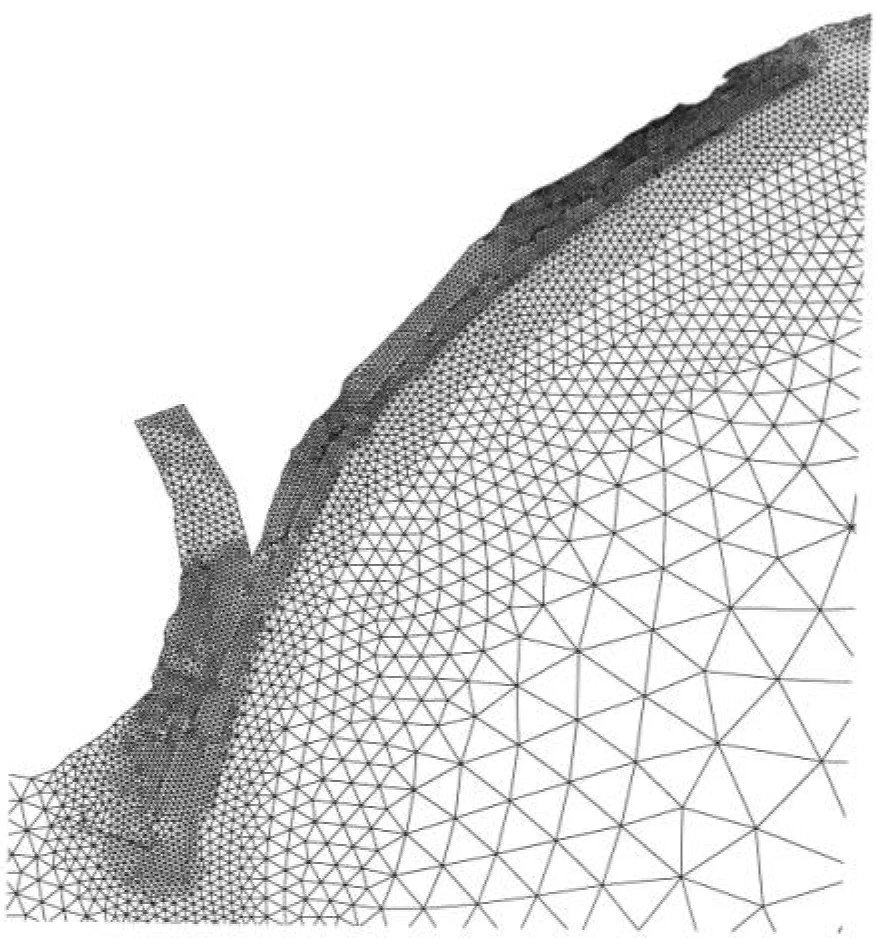
(3). Providing accurate and efficient computations over time periods ranging from months to years.

The ADCIRC model uses a finite-element algorithm in solving the defined governing equations over complicated bathymetry encompassed by irregular sea and shore boundaries. This algorithm allows for extremely flexible spatial discretizations over the entire computational domain and has demonstrated excellent stability characteristics. The advantage of this flexibility in developing a computational grid is that larger elements can be used in the open ocean regions where less resolution is needed whereas smaller elements can be applied in the nearshore and estuary areas where finer resolution is required to resolve hydrodynamic details.

b. Model Applications. The ADCIRC model has been applied to numerous applications

(Scheffner et al, 1994 and Westerink et al, 1992) along the east coast of the United States, Gulf of Mexico, and Caribbean Sea. A truncated East Coast version (extending from mid-Florida to Nova Scotia) of the grid was modified to provide high resolution of the North Carolina coastline from Onslow Beach, south to Cape Fear and up the Cape Fear Estuary. Topography for this entire area was specified according to available charts used in a previous study. Specific topography for the dune and berm system for Topsail, Carolina, and Kure Beaches was obtained from the Wilmington District and incorporated into the computational grid shown in **Figure 3B-1**.

Figure 3B-1 Detail of Refined Grid of the Study Area



3. Hurricane Wind Field Model.

a. Model Type. The hurricane wind field model used in conjunction with the ADCIRC model is the Planetary Boundary Layer (PBL) model developed by Cardone (Cardone, Greenwood, and Greenwood 1992). This model simulates hurricane-generated wind and atmospheric pressure fields by solving the equations of horizontal motion which have been vertically averaged through the depth of the planetary boundary layer. Additionally, a moving coordinate system is defined such that its origin always coincides with the moving low-pressure center of the eye of the storm.

b. Model Characteristics.

(1). The PBL model computes a stationary wind and pressure field distribution corresponding to hurricane parameter input computed from the National Oceanic and Atmospheric Administration (NOAA) National HUrricane Center's DATabase (HURDAT) of tropical storm events (Jarvinen, Neumann, and Davis 1998). This database contains all hurricane, tropical storm and severe tropical depression data that impacted the east coast, Gulf of Mexico and Caribbean Sea from 1886 to present. The database contains latitude and longitude locations of the eye of the storm event and the corresponding central pressure and maximum wind speeds. Data files corresponding to Hurricanes Fran and Bertha are shown in **Tables 3B-1** and **3B-2**. These data are adequate to compute all required input for the PBL model. Example plots of the track of Hurricanes Fran and Bertha extracted from the HURDAT database are shown in **Figures 3B-2 and 3B-3**. The date shown on the inset figure just prior to landfall is with respect to Greenwich Mean Time and corresponds to Tables 3B-1 and 3B-2.

Table 3B-1 HURDAT Database for Hurricane Fran

Date (m/d) 1996	0000 (Hr)				0600 (Hr)			
	Lat.	Long.	Speed	Pressure	Lat.	Long.	Speed	Pressure
8-23	00.0	00.0	0	000	00.0	00.0	0	000
8-24	14.2	24.8	25	1010	14.2	26.6	30	1009
8-25	14.1	30.8	25	1009	14.3	32.0	25	1009
8-26	14.9	37.0	25	1009	15.1	38.6	25	1009
8-27	14.9	42.7	30	1007	14.7	43.8	30	1006
8-28	14.6	47.5	45	1002	15.0	49.1	50	1000
8-29	16.4	53.7	65	987	17.0	55.0	65	987
8-30	19.1	58.5	65	991	19.4	59.4	65	991
8-31	20.5	60.9	60	988	20.8	61.2	60	987
9-1	21.7	62.1	65	978	21.9	62.6	65	982
9-2	22.9	64.7	75	978	23.3	65.7	75	976
9-3	24.2	69.0	75	977	24.4	70.1	80	975
9-4	25.7	73.1	95	961	26.4	73.9	100	953
9-5	28.6	76.1	105	946	29.8	76.7	105	952
9-6	33.7	87.0	100	954	35.2	78.7	65	970
9-7	39.2	79.9	30	1000	40.4	80.4	30	1001
9-8	42.8	80.1	30	999	43.4	79.9	30	999
9-9	44.9	75.9	25	1002	45.4	74.0	20	1004
9-10	46.7	70.0	15	1010	00.0	00.0	0	0
Date (m/d) 1996	**1200 (Hr)**				**1800 (Hr)**			
	Lat.	**Long.**	**Speed**	**Pressure**	**Lat.**	**Long.**	**Speed**	**Pressure**
8-23	14.0	21.0	25	1012	14.1	22.8	25	1011
8-24	14.1	28.2	30	1009	14.1	29.6	30	1009
8-25	14.6	33.4	25	1009	14.7	35.1	25	1009
8-26	15.3	40.0	30	1009	15.2	41.4	30	1008
8-27	14.6	44.9	35	1005	14.6	46.1	40	1004
8-28	15.5	50.7	55	995	15.9	52.3	60	990
8-29	17.8	56.3	65	988	18.6	57.5	65	988
8-30	19.8	60.1	65	989	20.2	60.6	60	990
8-31	21.1	61.4	65	984	21.5	61.7	65	983
9-1	22.2	63.2	70	982	22.5	63.9	75	981
9-2	23.6	66.7	75	976	23.9	67.9	75	976
9-3	24.7	71.2	80	973	25.2	72.2	85	968
9-4	27.0	74.7	105	956	27.7	75.5	105	952
9-5	31.0	77.2	100	954	32.3	77.8	100	952
9-6	36.7	79.0	40	985	38.0	79.4	30	995
9-7	41.2	80.5	30	1001	42.0	80.4	30	1000
9-8	44.0	79.0	25	1000	44.5	77.6	25	1001
9-9	45.7	72.3	15	1006	46.0	71.1	15	1008
9-10	00.0	00.0	0	0	00.0	00.0	0	0

Table 3B-2 HURDAT Database for Hurricane Bertha

Date (m/d) 1996	0000 (Hr)				0600 (Hr)			
	Lat.	Long.	Speed	Pressure	Lat.	Long.	Speed	Pressure
7-5	0.98	34.0	30	1009	10.2	36.3	30	1008
7-6	12.7	43.9	35	1005	13.1	46.6	35	1004
7-7	14.9	52.9	50	999	15.6	54.8	55	997
7-8	17.0	60.1	75	988	17.5	61.8	75	985
7-9	19.4	66.1	80	970	20.3	67.7	100	960
7-10	23.6	72.6	85	969	24.5	74.0	80	971
7-11	27.5	76.4	75	968	38.3	76.8	75	972
7-12	30.7	78.3	70	982	31.2	78.6	70	984
7-13	35.0	77.6	65	993	36.7	77.0	60	993
7-14	42.1	71.9	60	994	44.1	69.0	55	995
7-15	48.0	57.0	50	995	49.0	52.0	45	996
7-16	57.5	42.5	40	991	58.5	42.5	40	988
7-17	60.0	40.0	40	993	60.5	39.0	35	1001
Date (m/d) 1996	1200 (Hr)				1800 (Hr)			
	Lat.	Long.	Speed	Pressure	Lat.	Long.	Speed	Pressure
7-5	11.0	39.0	35	1007	12.0	41.2	35	1006
7-6	13.7	48.7	40	1002	14.2	51.0	45	1000
7-7	16.4	56.9	60	995	16.5	58.4	70	992
7-8	18.0	63.5	70	983	18.6	64.9	75	978
7-9	21.4	69.4	100	965	22.5	71.1	90	967
7-10	25.4	75.3	80	968	26.4	75.8	80	966
7-11	29.2	77.5	75	977	30.0	78.0	70	980
7-12	32.2	78.4	85	975	33.6	78.1	90	974
7-13	38.3	76.1	60	994	40.2	74.5	60	994
7-14	46.0	66.0	50	995	47.0	62.0	50	995
7-15	51.0	47.0	40	996	54.0	44.0	40	996
7-16	59.5	42.0	45	988	59.8	41.0	45	985
7-17	00.0	00.0	0	0	00.0	00.0	0	0

Figure 3B-2 Tracks of Hurricane Fran

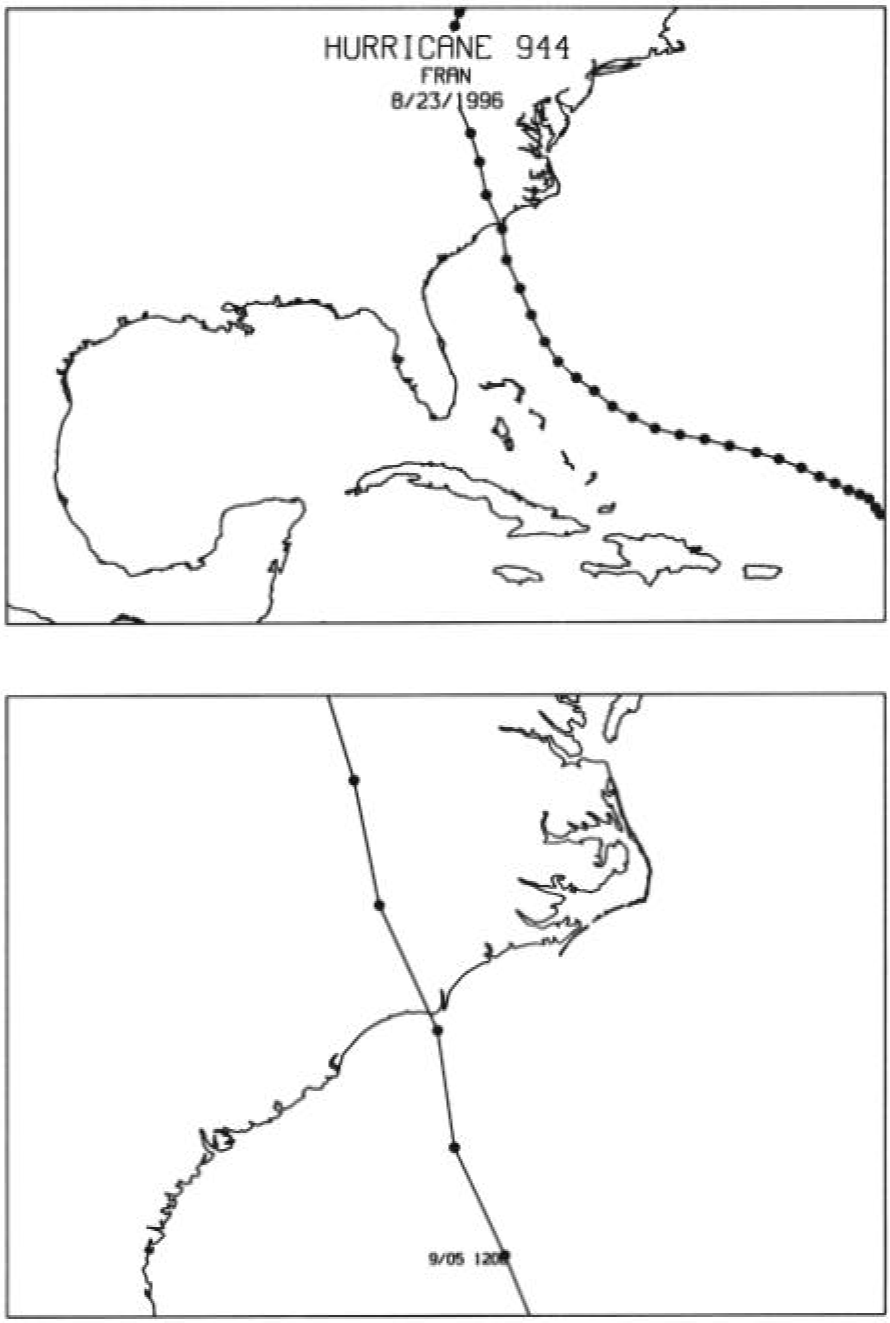
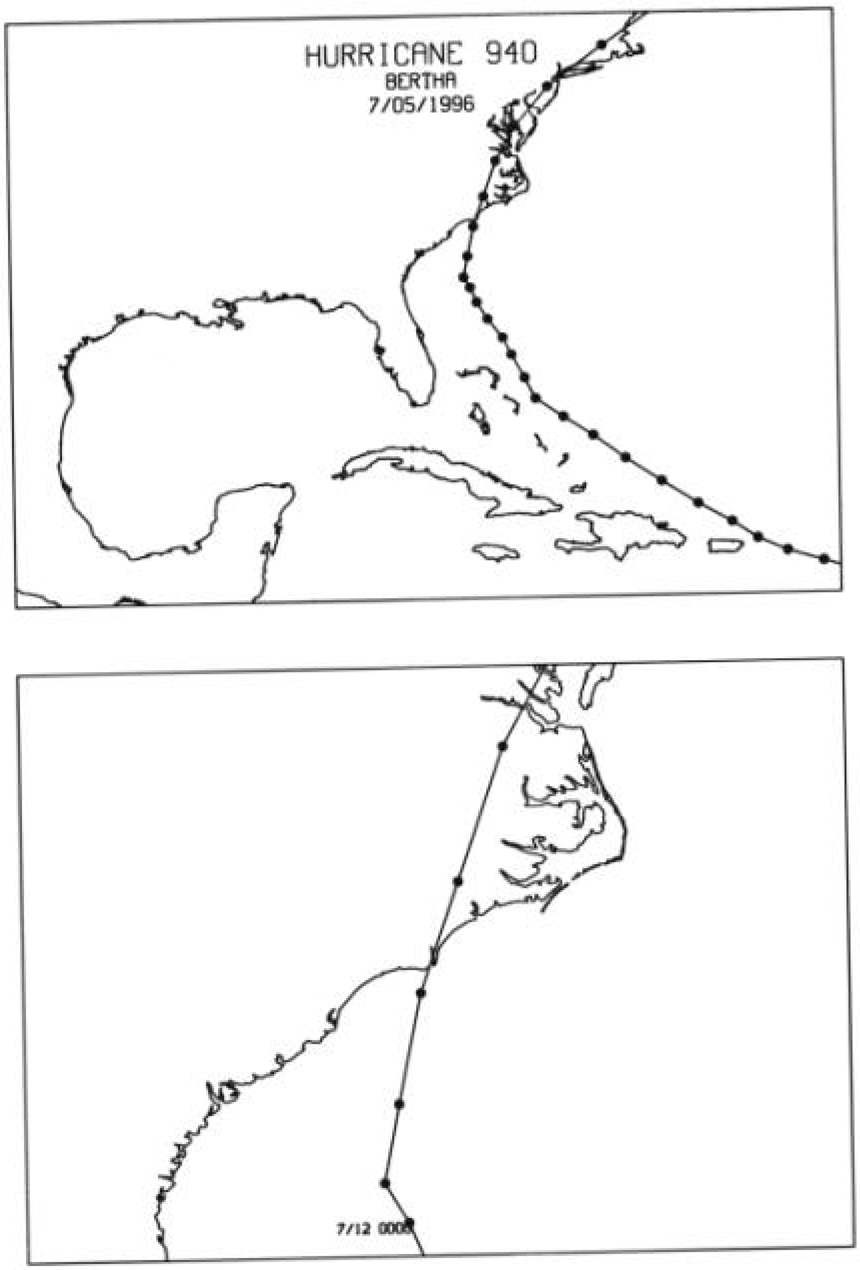


Figure 3B-3 Tracks of Hurricane Bertha



4. Storm Surge Modeling Results.

a. Maximum Storm Surge Elevations. Modeling of Hurricanes Fran and Bertha was initially conducted by simultaneously computing tide and storm surge. For the case of Hurricane Fran, the peak surge occurred near low tide, therefore a small surge was generated as evidence by the surface elevation time series for tide-plus-surge for Topsail Beach shown in **Figure 3B-4**. Conversely, Hurricane Bertha occurred near high tide as shown by the time series for Topsail Beach shown in **Figure 3B-5**. In order to make a meaningful comparison of surge impact, simulations described below are for Hurricane Fran without tide (i.e., **Figure 3B-6** for Topsail Beach) and Hurricane Bertha with tide. **Table 3B-3** shows the maximum storm surge computed for the four beaches of interest for both hurricanes. Maximum water surface elevations shown in Table 3B-3 give an indication of local maximum surge values for each location. Looking at the maximum surge elevation computed for any time during the hurricane simulation period shows an indication of the spatial distribution of maximum surge for the general area. Maximum surge distribution maps are shown in **Figures 3B-7** and **3B-8** for Hurricanes Fran and Bertha. Note that elevations are in meters, MSL (1.0 meter equals 3.28 feet).

Table 3B-3: Modeled Maximum Storm Surge Elevations

Station	Hurricane Fran Maximum Surge (without tide) (ft-msl)	Hurricane Bertha Maximum Surge (with tide) (ft-msl)
Kure Beach	5.1	4.6
Carolina Beach	5.3	4.8
Wrightsville Beach	6.0 [1]	5.0 [1]
Topsail Beach	4.8	4.3

[1]. Based on topography from the Brunswick Nuclear Power Plan Study by Norman W. Scheffner (WES).

b. Summary of Results. Inspection of Table 3B-3 shows that the modeled surge elevations for both Hurricanes Fran and Bertha are slightly greater at the protected Carolina and Wrightsville Beaches than for the unprotected Kure and Topsail Beaches. Although the differences are not significant, increased elevations are probably due to both the track of the storm and the focusing of bathymetry in the center of Onslow Bay shown in **Figure 3B-9**. The primary conclusion of this investigation, based on hurricane Fran and Bertha simulations, is that surge elevations for both events do not vary greatly over the study area. This non-variability results from the path of the storm and the similarity of offshore bathymetric contours.

Figure 3B-4: Surface Elevation Time Series for Hurricane Fran with Tide

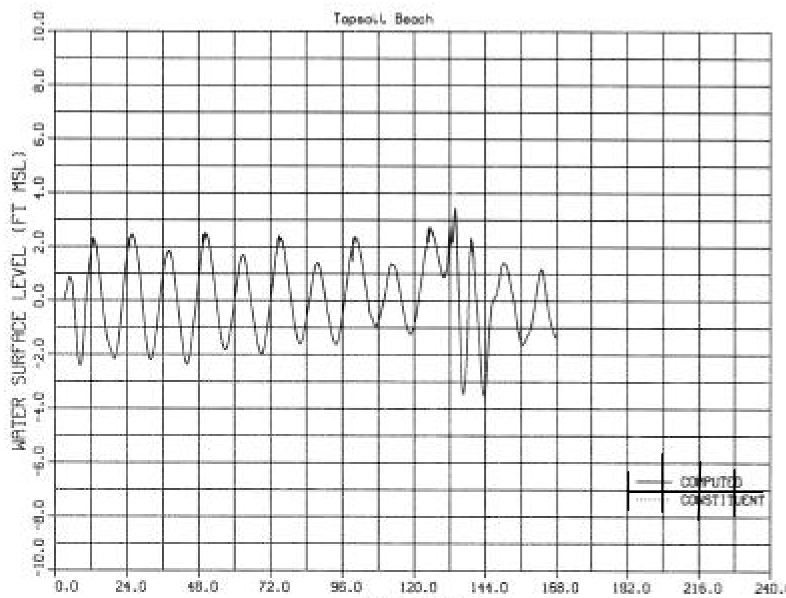


Figure 3B-5: Surface Elevation Time Series for Hurricane Bertha with Tide

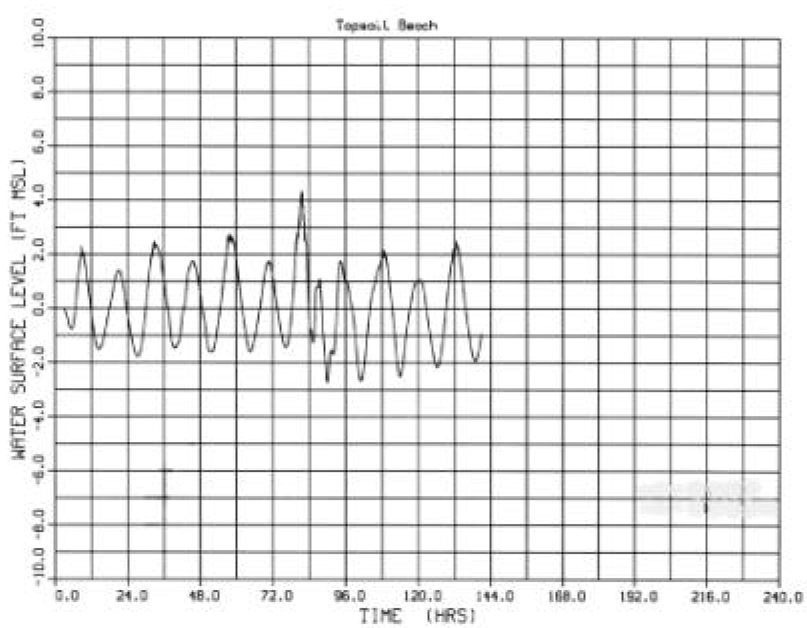


Figure 3B-6: Surface Elevation Time Series for Hurricane Fran Without Tide

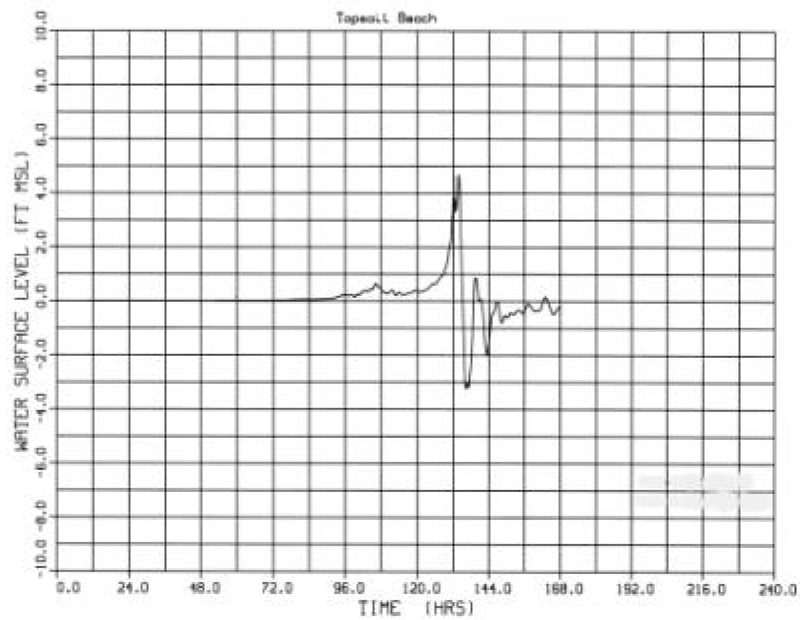


Figure 3B-7: Maximum Surge Distribution for Hurricane Fran

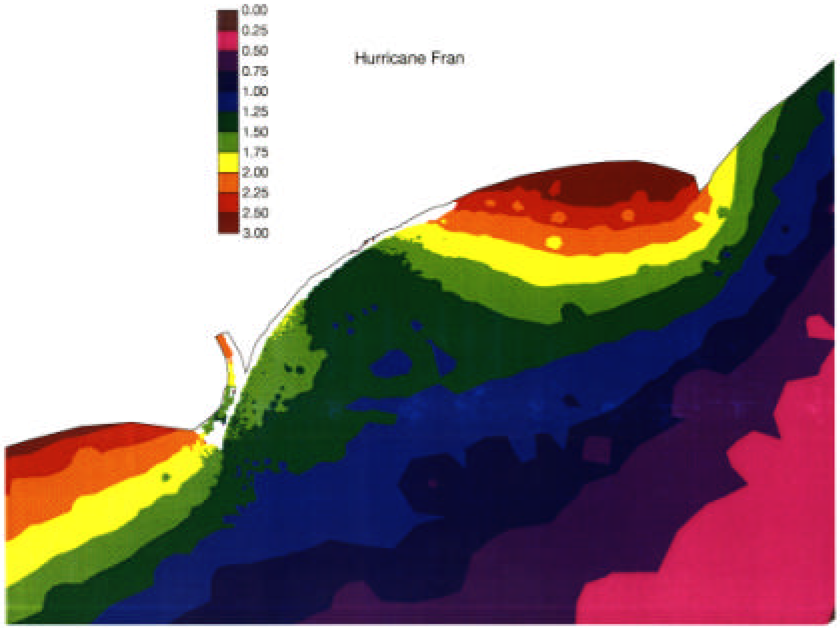


Figure 3B-8: Maximum Surge Distribution for Hurricane Bertha

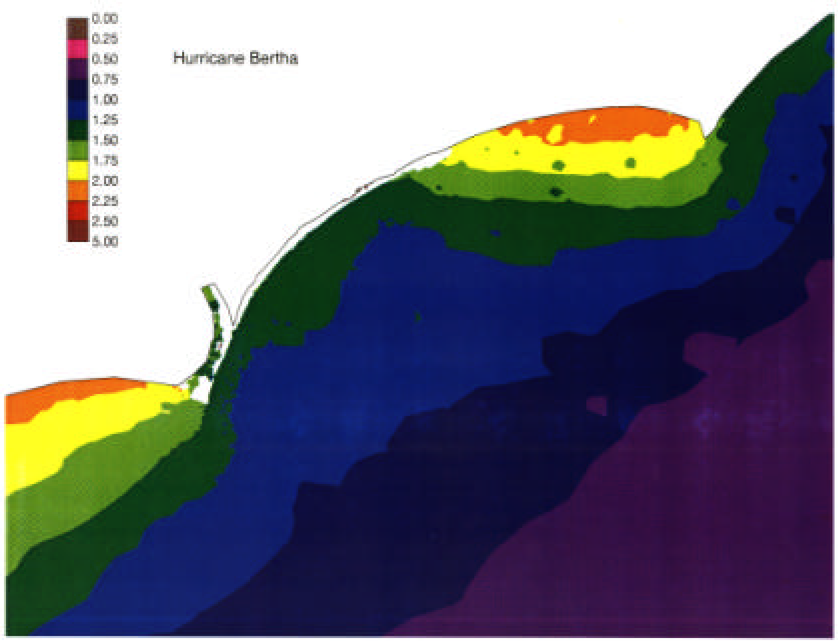
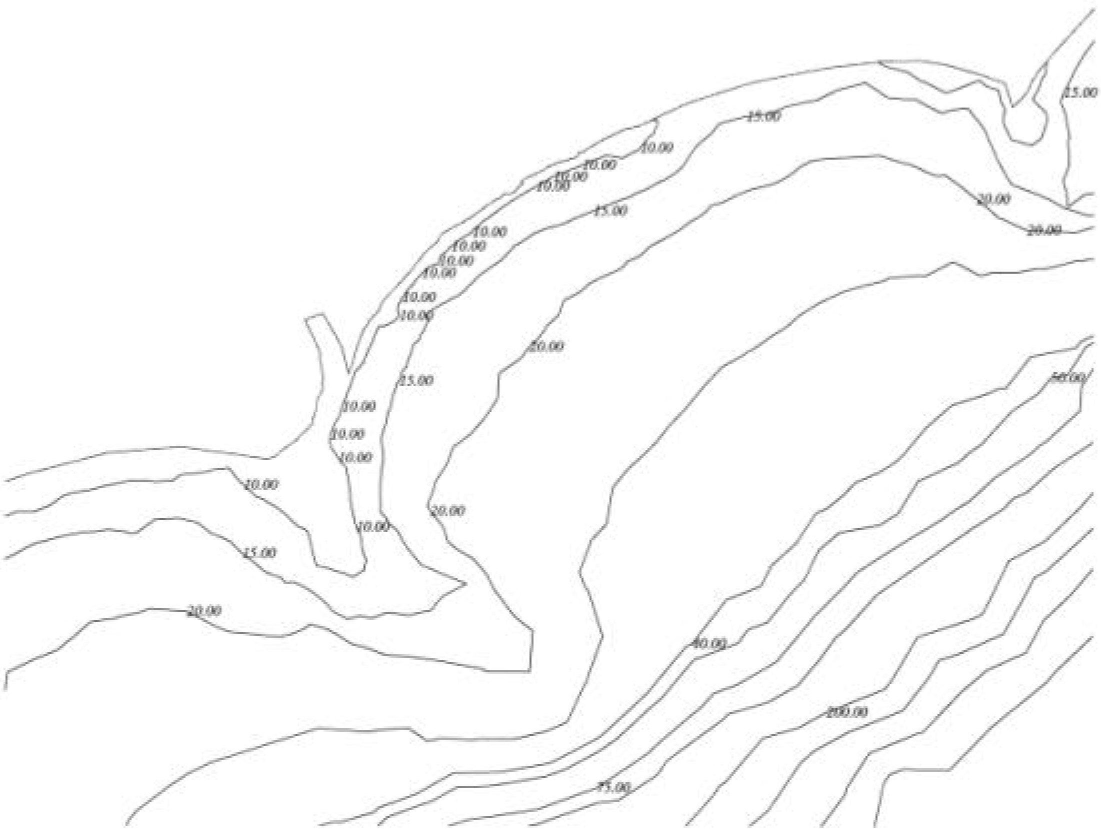


Figure 3B-9: Offshore Contours of Onslow Bay



5. References.

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Scheffner, N.W., Mark, D.J., Blain, C.A., Westerink, J.J., and Luettich, R.A., 1994, "ADCIRC: An Advanced Three-Dimensional Circulation Model for Shelves, Coasts and Estuaries Report 5: A Tropical Storm Data Base for the East and Gulf of Mexico Coasts of the United States," Technical Report DRP-92-6, August 1994, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Westerink, J. J., Luettich, A. M., Baptista, A. M., Scheffner, N. W., and Farrar, P. 1992, "Tide and Storm Surge Predictions using Finite Element Model," Journal of Hydraulic Engineering, ASCE, Vol. 118, No. 10. pp. 1373-1390.

C. WAVES

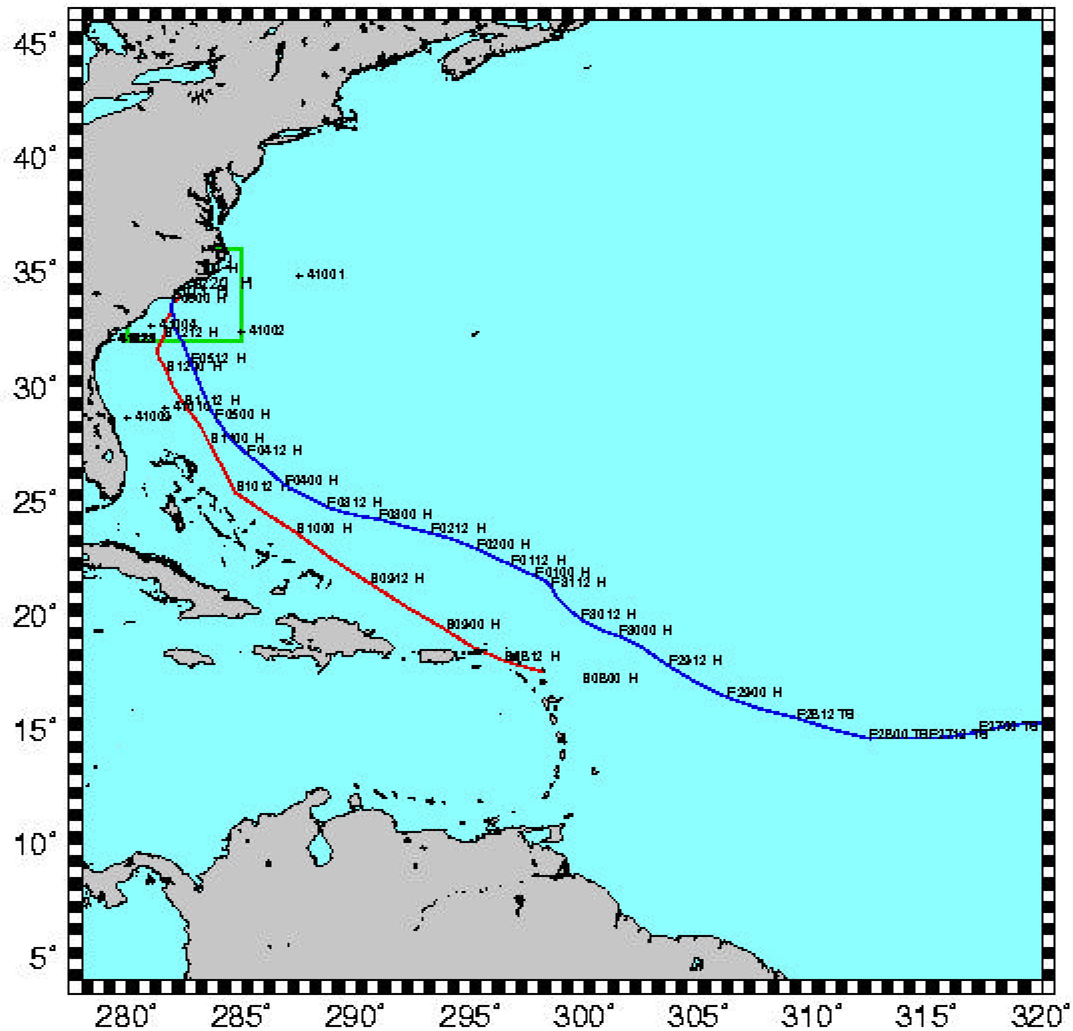
1. Introduction. The goal of this study is to determine the impact of the coupling of surge and wave effects generated by hurricanes Bertha and Fran at Kure Beach, Carolina Beach, Wrightsville Beach and Topsail Island. The assessment is based on results obtained from storm surge simulations using ADvanced CIRCulation (ADCIRC) (see previous Paragraph 3B) and wave modeling efforts using two modeling technologies, WAve Model (WAM) (Komen et al. 1994), and STeady WAVE (STWAVE) (Smith et al. 1999) driven by high resolution wind fields. Hurricane Bertha and Fran both had a very similar storm track and their intensity varied slightly in the context of tropical systems (**Figure 3C-1**). Storm intensities for the two storms are shown in **Table 3C-1**. Cape Fear is about 5 miles south of Kure Beach.

Table 3C-1: Storm Intensities

Storm	Maximum Sustained Wind (mph)	Minimum Pressure (mb)	Location of Landfall	Landfall Wind (mph)	Landfall Pressure (mb)
Bertha	115	960	Midway between Wrightsville Beach and Topsail Beach	104	974
Fran	120	946	Near Cape Fear	115	954

2. Wind Field Development. The estimation of wind fields for tropical storm wave simulation is a very critical element. The wind fields used in this study were generated by Oceanweather, Inc. using a combination of machine (derived from atmospheric models), measurements (buoy, ship observations), satellite (scatterometer), and aircraft reconnaissance through-flights carried out by the Air Force (Hurricane Hunters) as well as research flights performed by the National Oceanic and Atmospheric Administration (NOAA). The procedure is to take a set of background wind fields defined by a prescribed domain at a time interval dictated by the original winds. In this case the National Center for Environmental Predictions (NCEP) aviation wind model results were used as background wind fields at a time step of 6 hours. Using Oceanweather's tropical cyclone planetary boundary layer model and input criteria for each hurricane (central pressure, radius to maximum wind, and forward speed) a moving vortex describing the highly complex wind fields in a hurricane at resolutions to approximately 2km. From this point, an Interactive Objective Kinematic Analysis System (Swail and Cox, 2000) was used to assimilate all available measurements into the background winds. The measured winds were transformed to a standard height of 10m along with the background winds. The final product for Bertha and Fran were 10 minute average wind fields generated on a fixed latitude / longitude grid with resolution of 0.25° covering the domain from 4° N to 46° N Latitude, 278° E to 320° E Longitude at 1-hour time steps as shown on Figure 3C-1. In addition, surface pressure fields were generated for both hurricanes to be used in the surge modeling effort.

Figure 3C-1: Storm Tracks for Hurricane Bertha and Fran with Regional Domain for WAM



3. Wave Modeling Procedures.

a. Introduction. The wave modeling effort was performed in two stages, using two modeling technologies, WAM (Komen et al 1994) for the basin, region, and sub-region scales of the project. For the nearshore domain STWAVE (Smith et al 1999) was used and coupled to the surge estimates generated by ADCIRC.

b. <u>WAM</u>.

(1). WAM is a third-generation model, where no a priori assumptions governing the spectral shape are applied as in the case of second-generation models. See **Appendix D, Page D-3** for additional information on the modeling technologies. WAM was originally built for global scale operational wave forecasting purposes over a 10-year time period, (Komen et al 1994). During its development added options were introduced so that regional scale (e.g. continental shelf) applications could be performed. Multi-level grid nesting was introduced minimizing computational requirements. Thus, for coastal applications successively finer grids can be built focusing into a given domain. The far-field wave energy would be quantified in each successive grid domain via saving boundary condition information describing the 2-D spectrum over space and time. This was the procedure used in the Bertha and Fran wave modeling study.

(2). Input to WAM is a grid identifying the water depths and land masses (e.g. shorelines and offshore islands). Wind fields are introduced once the geographical information is generated along with other parameters for the time step, identification of the boundary conditions, and special output locations. This is summarized in **Table 3C-2**.

Table 3C-2: Definition of WAM Simulation Domains

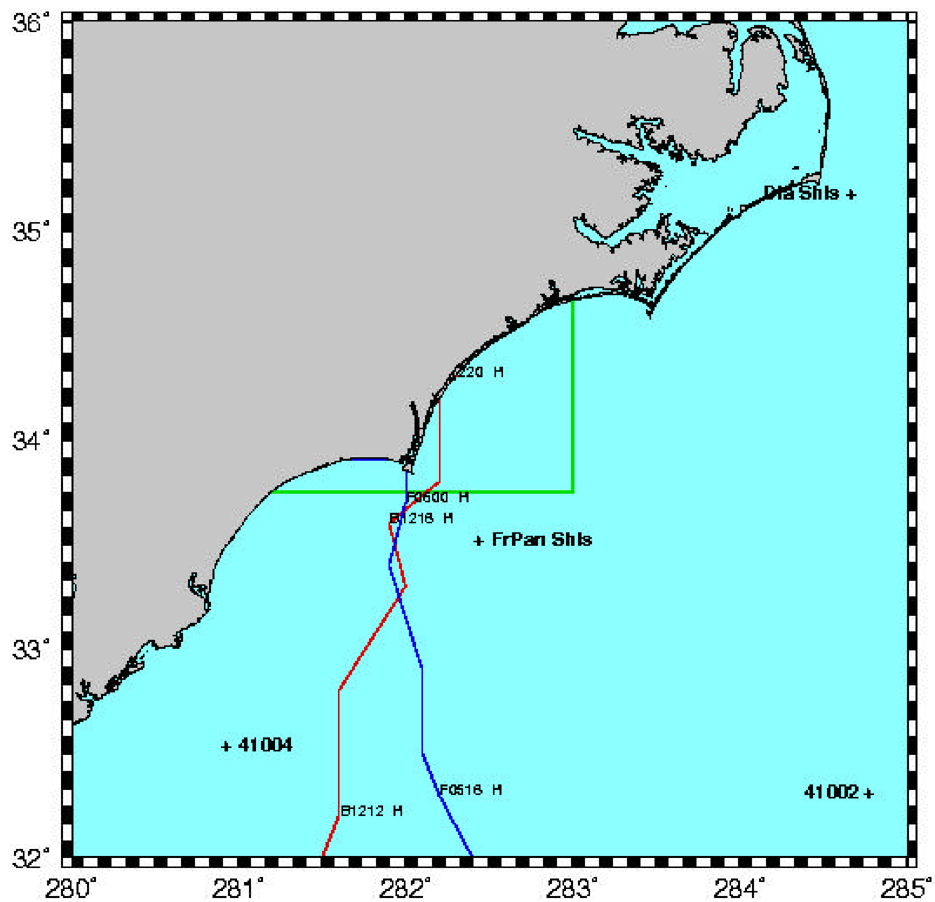
Domain Name	Latitude (° N)		Longitude (° E)		Resol (min)	Winds	BC
	South	North	West	East			
Basin	4.0	46.0	278.0	335.0	15	Original	OUT
Region	32.0	36.0	280.0	285.0	5	Interpolated	IN / OUT
Sub-Region	33.75	34.75	281.0	283.0	0.1	Interpolated	IN / OUT*

*2-D spectra generated for each of 3 STWAVE domains defined below.

The WAM basin simulation area was shown in Figure 3C-1. The regional domain is shown as the (bounded green) box. Nesting from the regional domain to the sub-region is shown in **Figure 3C-2.** Storm tracks for Bertha (red, labeled "B") and Fran (blue, labeled "F") along with sub-region domain defined by the green box. Wave gage sites (41002, 41004 and Frying Pan Shoals) derived from the National Data Buoy Center for verification of model results are also shown.

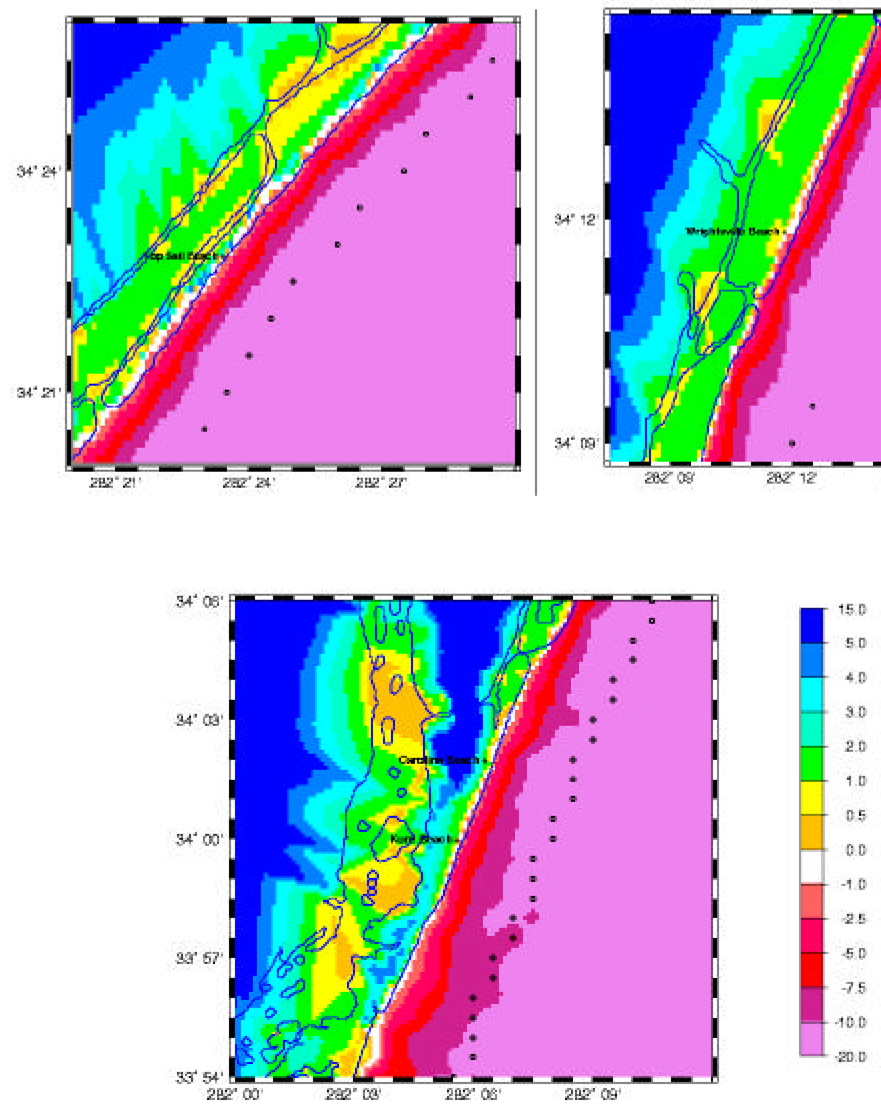
(3). For the WAM simulations, each higher resolution grid domain is forced by boundary condition information described via 2-D wave spectra at the coarse resolution's time step. The spectra are temporally and spatially interpolated onto the finer resolution's values noted in Table 3C-2. In addition, the wind fields are used in each of the prescribed domains. Within the sub-region domain there is one location offshore of each study area. Two dimensional wave spectra are generated, and used as the boundary condition information for the three STWAVE model domains.

Figure 3C-2: Regional WAM Simulation Domain



b. <u>STWAVE</u>. The STWAVE modeling domains were built using two data bases. For the offshore area, bathymetry were obtained from the National Ocean Service digital database. The elevation estimates were obtained directly from the ADCIRC refined grid. The data sets were then interpolated onto grids with spatial resolutions of 185.2m in x and y. One must note that all locations landward of the defined shoreline were assumed to be land. The net effect would only be evident if the surge levels from Bertha and Fran exceed the barrier island elevations. The STWAVE grid accuracy (**Figure 3C-3**) is dictated by the relative amount of quality information injected into the interpolation algorithm. For additional information on STWAVE see **Appendix D, Page D-3**.

Figure 3C-3: STWAVE Grid Domains
(Topsail Beach (upper left), Wrightsville Beach (upper right), and Carolina-Kure Beach (lower)) (elevation scale in meters**)**



4. Wave Model Verification.

a. Wave Measurement. Data for three active wave measurement sites (shown in Figure3C-2) are displayed in **Table 3C-3**. These sites provided wave data for verification of the WAM results

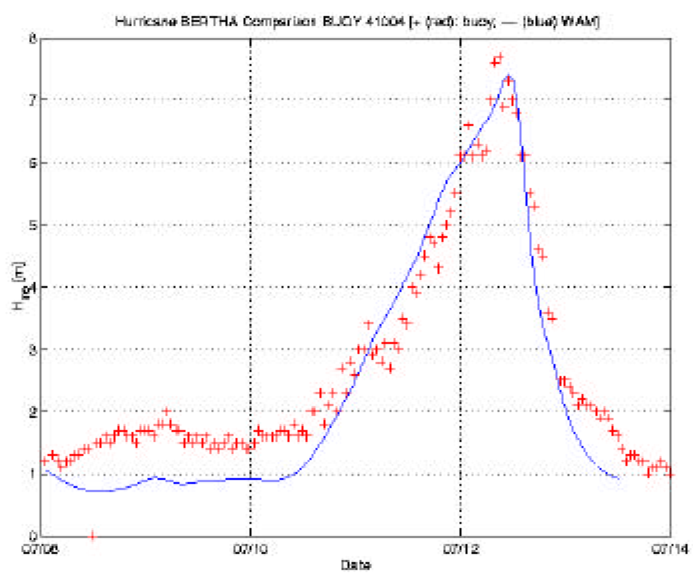
Table 3C-3: National Data Buoy Center Measurement Sites for Comparisons

Buoy Name	Longitude (East)	Latitude (N)	Depth (m)	Availability	
				Bertha	Fran
41002	284.80	32.28	3785.6	NO	YES
41004	280.90	32.51	36.6	YES	YES
Frying Pan Shoals	282.41	33.49	14	YES	YES

for Hurricanes Bertha and Fran. These sites are maintained by the National Data Buoy Center, NOAA. WAM results were compared to these sites for consistency in the wind estimates, and ultimately the wave estimates. Two of the measurement sites were situated to the east of Bertha and Fran's storm tracks (Figure 3C-2), while 41004 is located to the west. This provides a good basis for comparison, where typically the maximum winds (and largest) waves will reside, while the migration of swell energy will be evident in a down-wind and -wave direction at 41004. The range of water depths (from the maximum of 3800m to a minimum of 14m) provide further insights into the wave model's performance for arbitrary depth mechanisms such as refraction/shoaling, wave-bottom energy sinks, and depth limited breaking. Unfortunately no directional information in close proximity to the study area was available. These comparisons will provide a quality assurance in the wind fields generated by Oceanweather, Inc. as well as serve as a basis and the only basis of wave model verification for the subsequent finer scale WAM simulations as well as results generated for the three STWAVE domains.

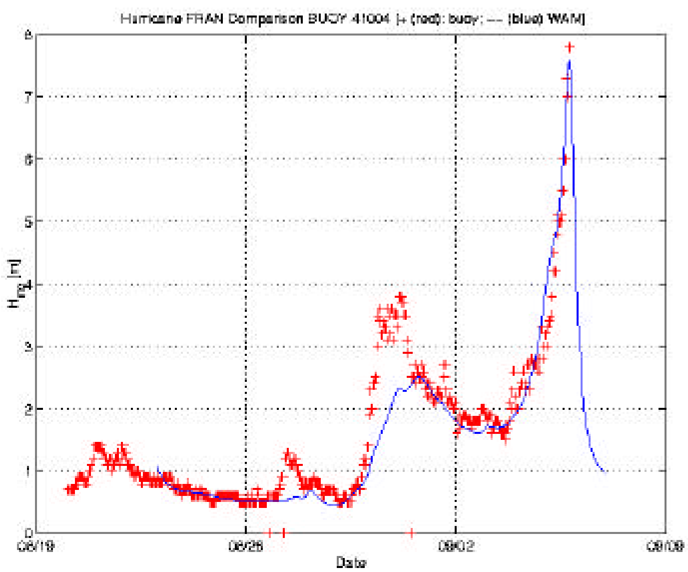
b. Bertha Regional WAM Comparisons. Three measurement sites were selected for wind and wave model verification during the Bertha simulation. The methodology used to construct the hurricane wind fields use all available wind data sources. Comparisons between the model winds to the measurements were virtually identical, and plots of model to measurements are omitted from this report. A more rigorous validation of the wind fields can be derived from wave model results compared to buoy measurements. Of course, any discrepancies between the WAM wave estimates and the measurements could be derived from inconsistencies in the winds as well as errors in the wave modeling technology used in the study. The comparisons between the WAM Bertha results and data obtained at the two active measurement sites are very good. In general the active growth cycle, and accompanying swells are well represented in the model results. The peak to peak comparison show that WAM under estimates by about 0.75-0.5m, and there is a slight phase shift in the peak of the model result of about 2 hours. Even during the decay cycle, where the height is diminishing at a rate of 1m/hr, WAM replicates the measurements. This demonstrates that the winds generated by Oceanweather, Inc. to drive the wave model are excellent, and that the WAM replicates the wave heights extremely well. **Figure 3C-4** displays time plots of comparisons between WAM and measurements for the energy based wave height for Hurricane Bertha at Buoy 41004. Additional data are contained in **Appendix D, Page D-4**.

Figure 3C-4: Wave Height Comparison for Hurricane Bertha Buoy 41004



c. Fran Regional WAM Comparisons. The storm track for Hurricane Fran was very similar to that of Bertha, but slightly to the west. Two (41002, and Frying Pan Shoals) of the three buoy locations were to the west of the hurricane path, providing an excellent data base to compare wave model results from very distinct quadrants in a tropical system. Two marked differences that separate Bertha from Fran were the winds, Fran being stronger, and that as Fran was in its development stages Hurricane Edouard was just off the U.S. coast. The initial peaks (occurring around 1 September) identify the influence of Hurricane Edouard at all three sites. Only a limited amount of work on the wind fields was focused on estimating the winds correctly for Edouard. That is the primary reason why the wave model results tend to under estimate the significant wave heights during that time period. During the time between 1-4 September the wave environment becomes very complex. Local generated (and swells) from Edouard would be combined with the early arriving swells from Fran, evident in the frequency spectra. Ultimately Fran and its accompanying 90-100kt winds dominate, producing measured significant wave heights ranging from 7.8m (41002) to 9.8m (Frying Pan Shoals). The change in wave heights over time was approximately 1m/3hr, typical of a very rapidly moving and growing storm. **Figure 3C-5** displays time plots of comparisons between WAM and measurements for the energy based wave height for Hurricane Fran at Buoy 41004. Additional data are contained in **Appendix D, Page D-5**.

Figure 3C-5: Wave Height Comparison for Hurricane Fran Buoy 41004



5. Sub-region WAM Simulation Results.

a. Significant Wave Height. Significant wave height color contour plots (**Figures 3C-6 and 3C-7**) were generated for the Bertha and Fran simulations. These results identify the spatial gradients in the H_{mo} of model results at the time of landfall. H_{mo} is a symbol used for the computed parameter "significant wave height." Significant wave height is the value that best "represents" the range of wave heights experienced at a particular place over a particular time period. The differences in intensity are evident comparing the WAM results of Bertha (Figure 3C-6) and Fran (Figure 3C-7). Maximum significant wave heights in excess of 16 m are evident in the Fran results, while Bertha's maxima are slightly over 10 m. In the nearshore area the H_{mo} model results are nearly uniform and peak at about 9 m for Fran, whereas, in the Bertha simulation, the general trend is approximately 7-8 m with pockets of 6 m heights along the Carolina-Kure Beach area and south. Bertha's landfall occurred between Wrightsville and Topsail Beach. This produced the strong lobe of energy to the east evident by the 10 m significant wave heights, and a slight but marked gradient to the west of Cape Fear and also to the north, near Cape Lookout. Hurricane Fran made landfall near Cape Fear, producing extreme wave conditions all along the North Carolina coastal waters stretching from near Onslow Bay the Kure Beach. Attenuation of the wave heights principally from depth induced wave breaking are found surrounding the Cape Fear area.

Figure 3C-6: Significant Wave Height Contour Plot During Landfall of Bertha

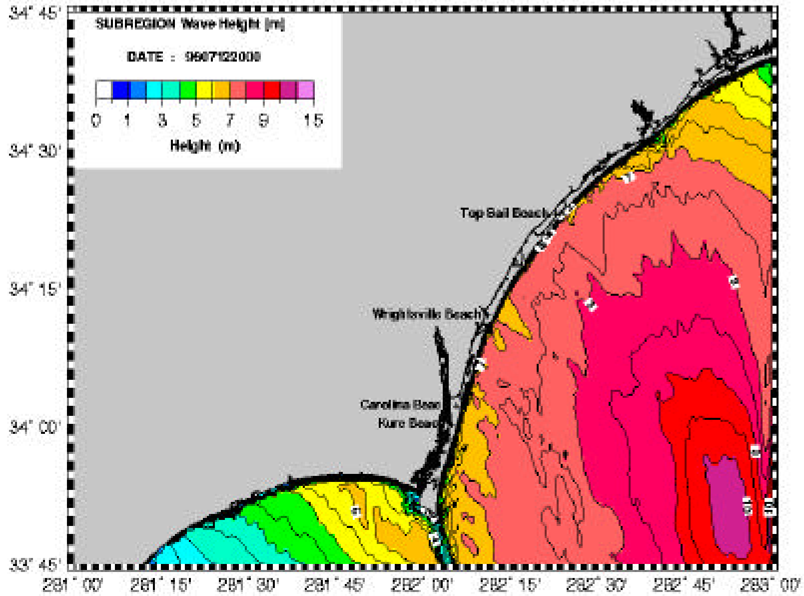
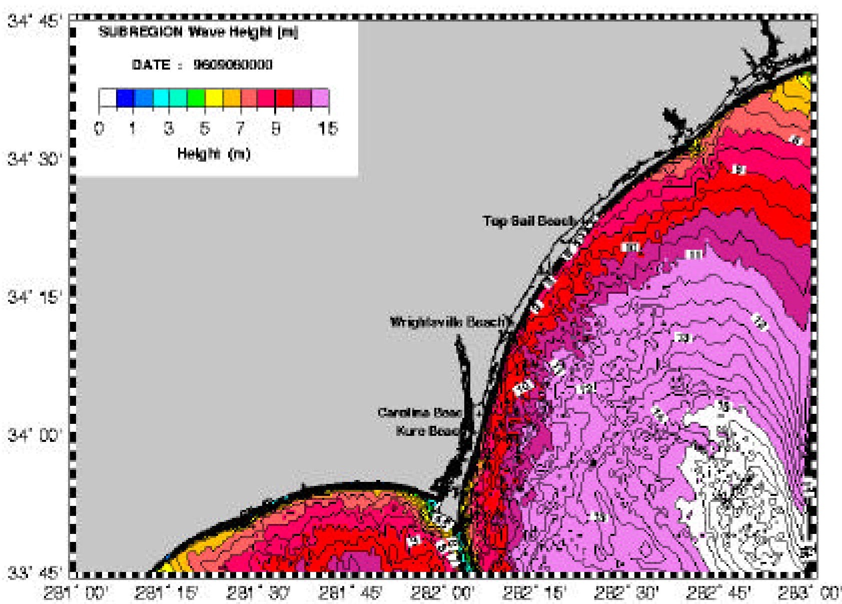


Figure 3C-7: Significant Wave Height Contour Plot During Landfall of Fran



.

b. Peak Wave Period.

(1). An obvious difference between the two results is the spatial variation in the H_{mo} contours of hurricane Fran. The primary cause of this can be found in **Figures 3C-8 and 3C-9**, peak spectral wave period (defined as the inverse of the frequency band containing the maximum energy in the 1-D spectra) contour plots. The WAM results clearly display peak spectral periods (T_p) in a range from 12 to a maximum of 15 sec occurring just to the northeast of the maximum energy lobe for Bertha (figure 3C-8). Depth induced mechanisms such as refraction, shoaling and the scaled source terms will become effective for the T_p range (12-15 sec) in water depths less than 20 m. The peak period range derived from Fran (Figure 3C-9) is markedly longer at 15 to 19 sec. Arbitrary depth mechanisms strongly affect the wave conditions for water depths less than 35 m. The highly variable bottom in the modeling domain and accompanying long period energy will generate the deviations in the modeled wave height estimates.

(2). To assess the impact of Bertha and Fran along the study area, WAM results were saved approximately 4 km from the shoreline, at about 1 km resolution from just north of Topsail Beach to slightly south of Kure Beach. The wave height estimates were plotted over location and time identifying the time and spatial variation for each of the two hurricanes for the entire simulation period. Because of the rapid movement of both Bertha and Fran only the last 60 hours of each simulation period were plotted. These results are shown **in Figures 3C-10 and 3C-11** for Bertha and Fran respectively. The WAM results for hurricane Bertha (Figure 3C-10) are indicative of the near homogeneous wave height wave estimates along shore evident from the single wave height contour plot (Figure 3C-6) at the peak of the storm. Despite Bertha making landfall between Wrightsville and Topsail Beach, H_{mo} values of 8 m were apparent for a near continuous time period south of Kure Beach. In addition, there is only a slight spatial wave height gradient toward the south. In general, the entire reach from Kure Beach to Topsail Beach was impacted by significant wave heights of about 8m. One may conclude from Figure 3C-10 that the shoreline reach from just south of Wrightsville Beach to Kure Beach were most severely affected.

(3). The results derived from Fran (Figure 3C-11) shows a very similar trend displayed for the Bertha simulation. Significant wave height estimates in general, were approximately 1-1.5m greater for Fran than Bertha. There were locations between Wrightsville and Carolina Beach that experienced H_{mo} estimates of 10 m. The spatial and temporal variations for Fran were virtually homogenous from Topsail to Kure Beach. These results are not surprising because of the hurricane path and that depth limited wave breaking was taking place. Water depths were on the order of 15 meters at these locations 4 km from shore.

(4). In summary, hurricane Bertha and Fran displayed very similar trends in the nearshore domain. Fran generated higher H_{mo} and longer T_p estimates in the offshore area, however the results derived from about 4 km from shore were fairly constant (in space and time) from Kure to Topsail Beach.

Figure 3C-8: Peak Wave Period Contour Plot During Landfall of Bertha

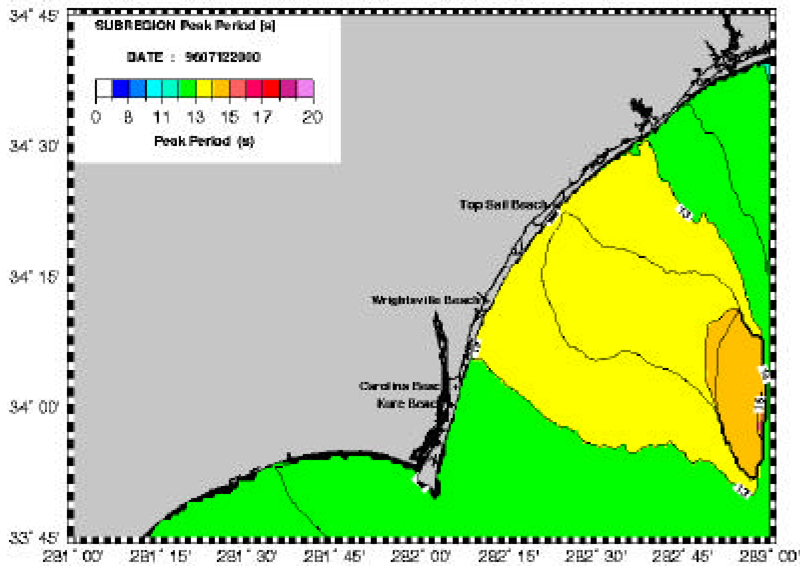


Figure 3C-9: Peak Wave Period Contour Plot During Landfall of Fran

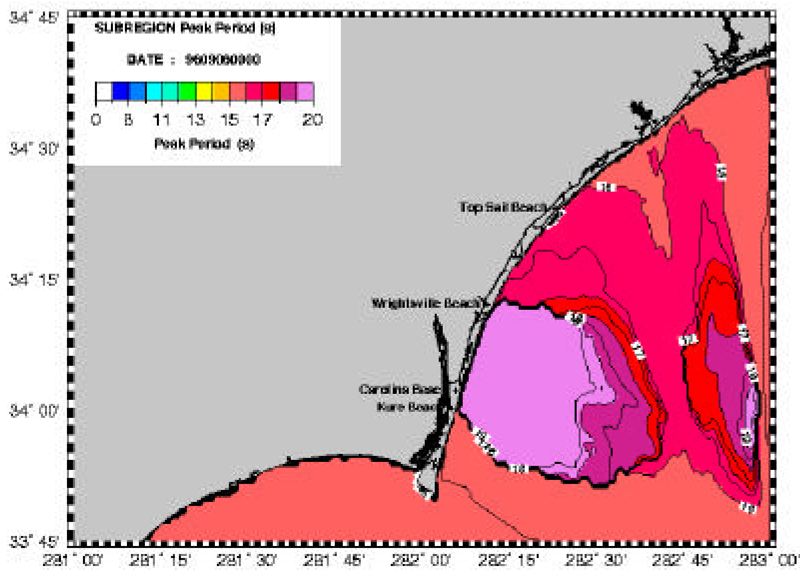


Figure 3C-10: Spatial (latitude) and Temporal Variation of H_{mo} During Bertha
(approximately 4 km offshore)

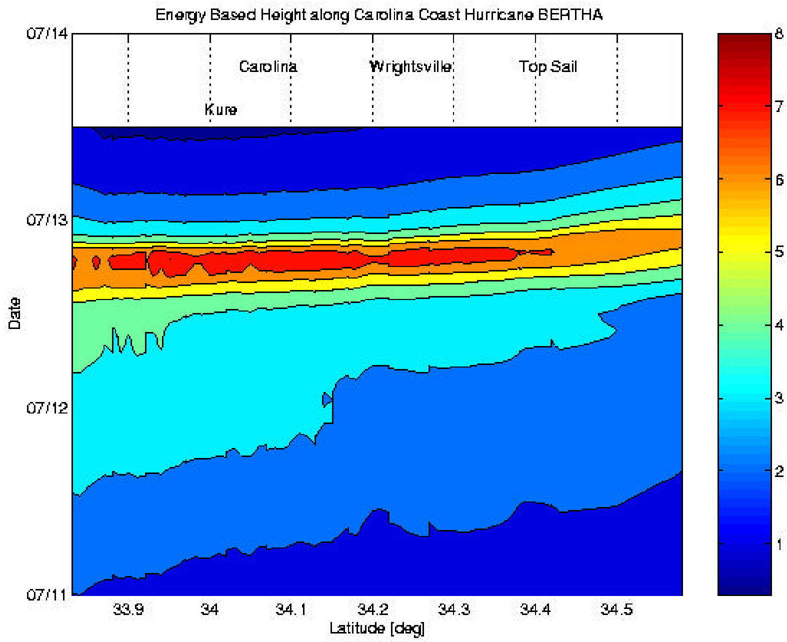
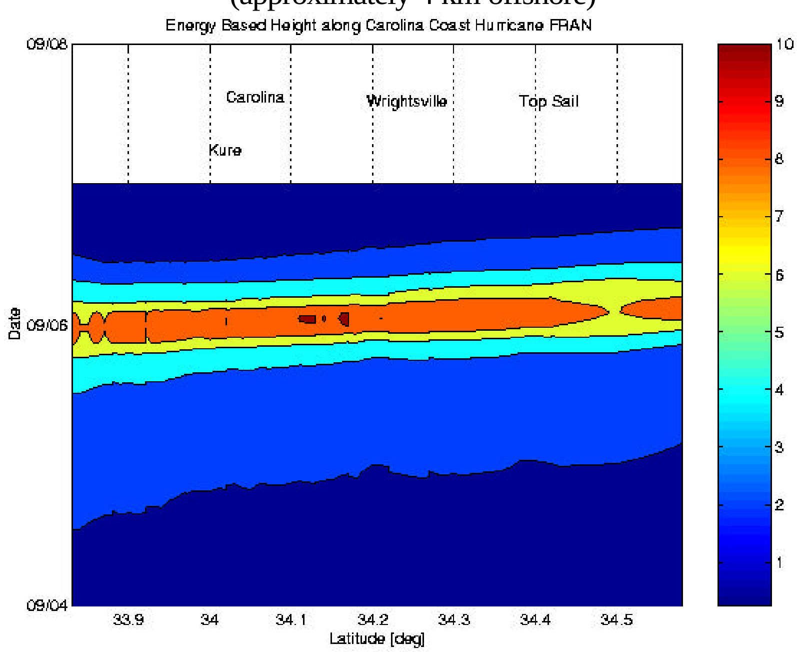


Figure 3C-11: Spatial (latitude) and Temporal Variation of H_{mo} During Fran
(approximately 4 km offshore)



6. Coupled Wave (STWAVE) and Surge Estimates.

a. Introduction. As previously stated, 2-D spectral estimates generated in the sub-region WAM domain were saved at offshore (approximately 5 km) locations from the 4 study sites. Once synthesized into the STWAVE coordinate system and truncated to a half-plane (Smith et al. 199), each of the hurricanes were processed for the area surrounding Kure, Carolina and Wrightsville Beaches and Topsail Island. In addition, surge estimates generated by ADCIRC were used to modify the water depth grids, overtopping the coastal landmasses during the time of maximum water level estimates. One must realize up to this point the resultant wave estimates have been dependent on the accuracy of the winds, the modeling technology and to a lesser extent the local bathymetry. It was shown that WAM replicates wave measurements at 3 sites. One can also conclude the winds generated by Oceanweather, Inc. represented hurricanes Bertha and Fran very accurately. One can presume, the WAM estimates for the sub-region would represent existing conditions because of the hurricane paths, that all 3 verification sites were south of the area, the wind forcing were derived from the original Oceanweather, Inc. fields and the modeling technology WAM was the same. Running at the sub-region domain introduces an unknown factor in the specification and accuracy of the bathymetry. In general, the net effect in the wave estimates running with inaccuracies of ±2-5 meters in the bathymetry would be negligible compared to the wind field specification. As in the case of the WAM sub-region simulation, the best form to present the final wave estimates are significant wave height color contour plots occurring at the peak of Bertha and Fran. Because of the rapid growth, and decay of the hurricanes in time, the energy levels decrease substantially ±1-2 hours either side of the storm peak, despite the level in the surge estimates. For additional information on the development of coupled wave and surge estimates, see **Appendix D, Page D-6**.

b. Coupled STWAVE-ADCIRC Hurricane Bertha Results.

(1). The coupled STWAVE-ADCIRC results are displayed in **Figures 3C-12, -13 and -14**, for Topsail, Wrightsville, Kure-Carolina Beach domains. Included in the figures are H_{mo} color contours, the mean wave direction (every 4th grid location), and the location of the shoreline. In addition, gray shaded areas depict the lateral extent of the surge effect. Again this is based on the provided elevation information for the landmasses. One also has to realize that all water domains landward of the barrier islands were not modeled, and assumed to be land.

(2). The wave height estimates at Topsail Beach (**Figure 3C-12**) clearly show a trend for attenuation of the offshore energy as it approaches the coastline. The wave height levels just offshore of Topsail are spatially invariant and are in a range of 2.5 to 3.0 meters. Despite a near uniform bottom across the model domain (Figure 3C-3), there is a very distinct energy pocket created. The mean wave direction attempts to approach the shoreline in a shore normal orientation, however, it tends slightly south close to the coast. Coupling the surge effect visibly moves the wave attack zone further landward, past the shoreline (represented by the red line). The maximum lateral movement occurs at two locations, south of the center line (identified in Figure 3C-12 by the Top Sail annotation), and at roughly 34° 24' latitude. It appears as though the maximum H_{mo} rarely exceeds between 1.0 to 1.5 meters on the barrier island.

(3). Moving south to Wrightsville Beach (**Figure 3C-13**) the simulated wave environment changes dramatically. The range in offshore wave heights are now from 3.5 to 4.0 meters, nearly a meter greater than at Topsail. Probably the most significant aspect in the Wrightsville Beach simulation is the large wave height gradients in close proximity to the shoreline. Within 1 km from the defined shoreline (the red line) H_{mo} estimates increase by 2 meters. From north of Masonboro Inlet (about 34° 11' latitude) to the northern extent of Wrightsville Beach, the energy level is more severe than what was evident in the Topsail area. The land mass now flooded (based on the ADCIRC estimates) is significantly greater compared to that of the Topsail reach.

(4). The Kure-Carolina Beach reach was modeled using one STWAVE domain (**Figure 3C-14**). One must realize the ADCIRC results were interpolated from the two sets of estimates to produce a unique temporally varying water level input file used during the STWAVE simulations. As indicated in the Storm Surge Modeling Section, the differences between Kure and Carolina were 0.061 meters (or 0.2 ft as identified in Table 3C-3). This should not produce marked differences in the wave estimates. For the Bertha simulation, the coupled STWAVE results show similar trends in the offshore wave climate experienced at Wrightsville Beach. The offshore H_{mo} results at Kure-Carolina Beach (Figure 3C-14) produced a larger aerial coverage of 6.0 meter conditions. Significant wave heights approximately 2 km from the shoreline were also elevated compared to the two previous STWAVE domains. However, the wave height gradients observed along Kure-Carolina Beach were uniform alongshore, and similar to that of Wrightsville. What is evident, is that the surge level did not migrate the attacking waves more than about 500 meters landward of the established shoreline. In addition, the shaded domains were substantially diminished compared to the coverage encountered at Topsail and Wrightsville beach. There is evidence of the migration north of Carolina Beach (34° 03' latitude), and further south near the 33° 54' latitude.

Figure 3C-12: Topsail Beach
Significant Wave Height Estimates Contours for Peak Storm Conditions, Hurricane Bertha
(arrows are the vector mean wave direction)

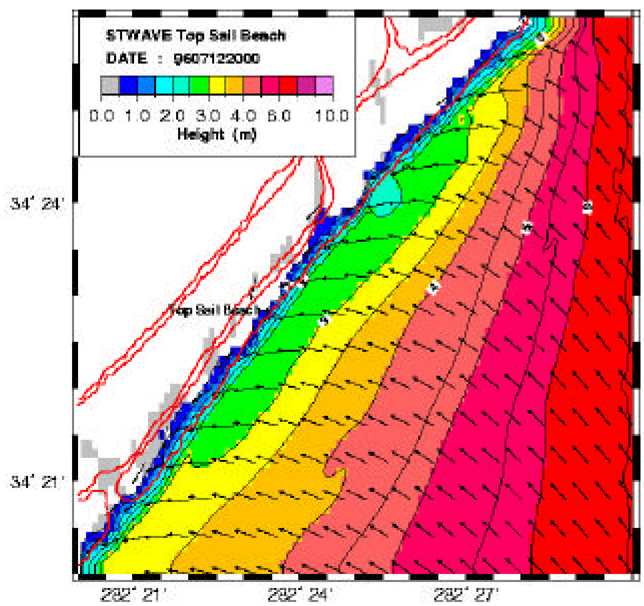


Figure 3C-13: Wrightsville Beach
Significant Wave Height Estimates Contours for Peak Storm Conditions, Hurricane Bertha
(arrows are the vector mean wave direction)

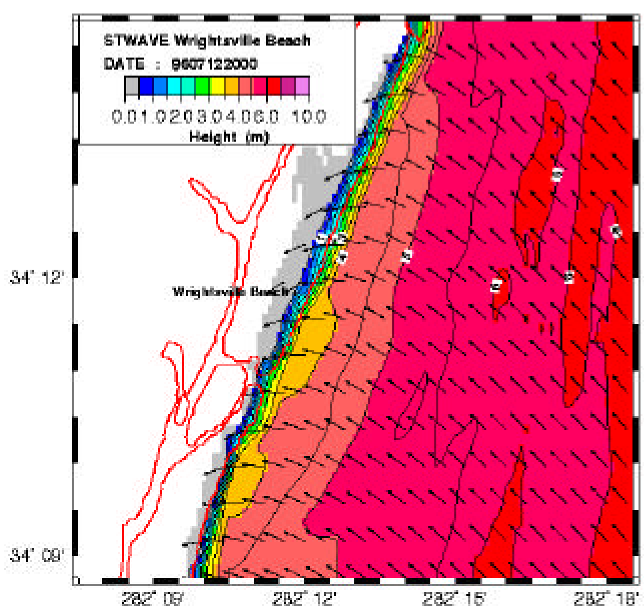
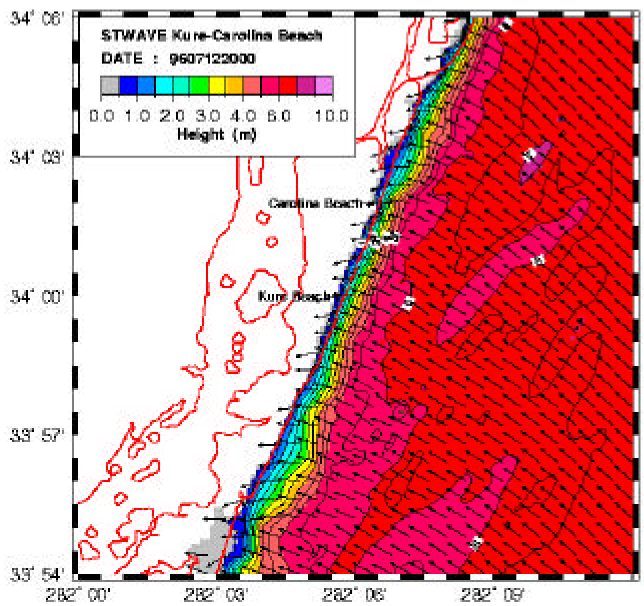


Figure 3C-14: Kure-Carolina Beaches
Significant Wave Height Estimates Contours for Peak Storm Conditions, Hurricane Bertha
(arrows are the vector mean wave direction)



(4). In summary, the results of the combined wave-storm surge simulations for Hurricane Bertha show:

(a). The most severely impacted shoreline reach was at Wrightsville Beach because of the landward migration of the wave estimates caused by the surge.

(b). The Kure-Carolina Beach domain were dominated by the largest wave conditions offshore, the gradients in wave height alongshore were uniform. Seaward the H_{mo} gradients were similar to that encountered at Wrightsville Beach, however the migration of the surge in a landward direction was significantly less.

(c). Topsail Beach was affected by the surge slightly less than at Wrightsville Beach, and more so than at Kure-Carolina Beach. The wave climate offshore was about 1-2 meters lower than at Wrightsville and Kure-Carolina Beaches.

c. Coupled STWAVE-ADCIRC Hurricane Fran Results.

(1). The coupled surge and spectral wave modeling effort for Hurricane Fran was run in a similar fashion as in the case of Bertha. The results of these simulations are shown on Figures **3C-15, -16 and –17** for, respectively, Topsail, Wrightsville and Kure-Carolina Beaches.

(2). In comparing the H_{mo} results of Fran and Bertha for topsail Island reveal a similar structure to the offshore wave climate. The Fran results are approximately 1.5 to 2.0 meters greater in significant height, however the banding of the contours from southwest to northeast is evident. There is evidence of the nearshore pocketing of H_{mo} estimates from 3.0 to 4.0 meters (the Bertha results were 2.5 to 3.0 meters). Lobes of higher significant wave heights (3.5 to 4.0 meters) appear just to the north and south of the centerline. Adding in the surge effects, the barrier islands are exposed to wave estimates ranging from 0.5 to a maximum of 1.5 meters. This is similar to that observed during Bertha, and the area of concentrated energy is nearly identical.

(3). At Wrightsville Beach the Fran simulation produced elevated significant wave heights of 2.0 to 3.0 meters greater than Bertha. The spatial distribution of H_{mo} differs from Bertha attributed in increased energy in the lower frequencies, and subsequent refraction and shoaling mechanisms. The offshore gradients in significant heights for the Fran simulation are very similar to that observed in the Bertha run, however the 5.0 meter contour is the seaward limit, rather than 3.5 for Bertha. Elevated H_{mo} values of 0.5 to 2.0 meters are evident all along the Wrightsville Beach shoreline.

(4). The offshore significant wave heights along Kure-Carolina Beach from the Fran simulation are again elevated by 1.0 to 3.0 meters. But in the nearshore one finds the position of all contours from 5.0 meters and lower to be nearly identical to that obtained from the Bertha simulation. Depth induced breaking limits the heights, despite the elevated (from 5 to 9 seconds) peak spectral wave period estimates from Fran compared to Bertha. The gradients from the land, seaward are extremely steep, and uniform from south of Kure Beach to the northern edge of Carolina Beach.

(5). In summary, the results of the combined wave-storm simulations for Hurricane Fran display the trends established in the Bertha simulation, however, in general the offshore wave climate for all three STWAVE domains were elevated from 1.0 to 3.0 meters.

Figure 3C-15: Topsail Beach
Hurricane Fran, Significant Wave Height Estimates for Peak Storm Conditions

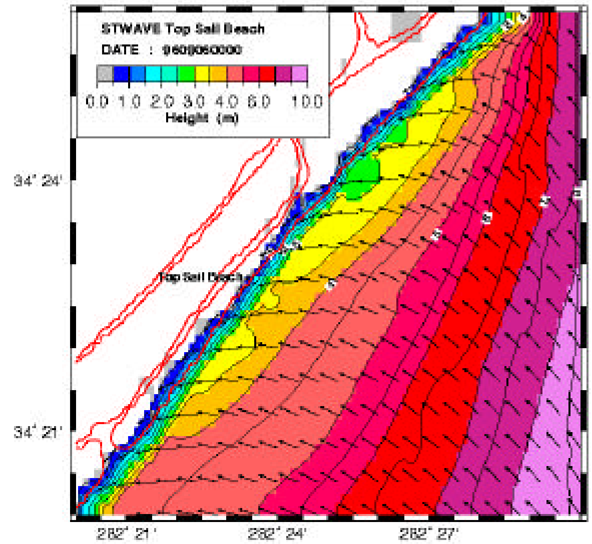


Figure 3C-16: Wrightsville Beach
Hurricane Fran, Significant Wave Height Estimates Contours for Peak Storm Conditions.

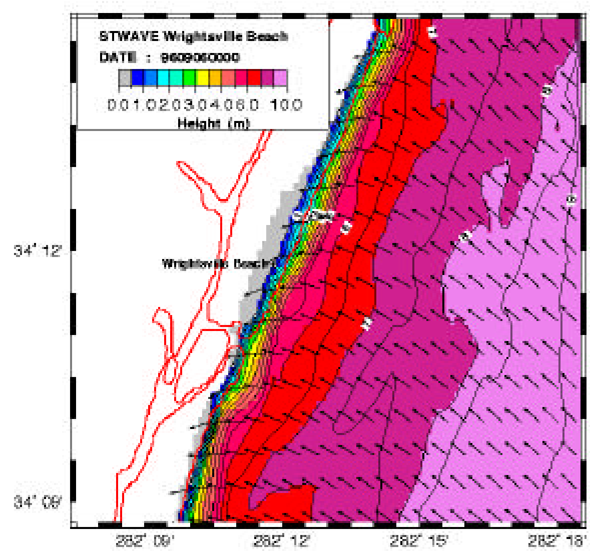
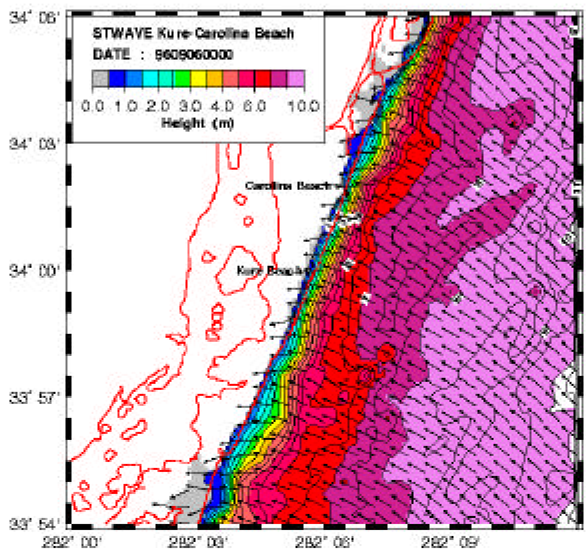


Figure 3C-17: Kure-Carolina Beaches
Hurricane Fran, Significant Wave Height Estimates Contours for Peak Storm Conditions



7. Modeling Summary.

a. Accuracy of Modeling Technology. The estimation of combined wave and surge effect for landfall hurricanes is dependent on many factors: the accuracy in the wind fields, wave and surge modeling technologies, accuracy in the offshore bathymetry, and ultimately the elevation of the land. This section demonstrated that winds generated by Oceanweather, Inc. provided the basis to accurately represent the offshore wave climate peak H_{mo} estimates within a range of 0.5 to 0.75 m. One can also conclude the wave modeling technology WAM (Komen et al 1994) used for hurricane simulations can accurately depict these highly complex meteorological, and wave scenarios. Pushing a wave model originally built for global (e.g. oceanic basins at spatial resolutions of 1°) into the regional (5' spatial resolutions), and ultimately sub-region (about 1') is a viable alternative and can be done without loss in accuracy.

b. Verification of Offshore Wave Climate. Estimates in the offshore wave climate were verified to three measurement sites south of the study area. One can conclude WAM represented the wave climate of Bertha and Fran accurately, and depicts the existing wave environment of both sides of these fast moving tropical systems. This is generally not the case for typical hurricane simulations. The right quadrant is generally modeled accurately, while the left quadrant is poorly represented. Again, most of the accuracy in the wave estimates is derived from accurate wind estimates. The verification locations were south of the study area. Hurricane Bertha and Fran were moving in a northerly direction, thus one can suggest the accuracy in the wave estimates found in the regional domain would be evident in the sub-region domain.

c. Results of Sub-regional WAM Simulations. Results derived from the sub-region WAM simulations show a general trend for the offshore wave climate (about 4 km from shore) to be relatively homogeneous from Cape Fear to just south of Topsail Beach during Bertha (Figure 3C-12). The peak H_{mo} conditions for Bertha was in a range from 7.0 to 8.0 meters. The peak conditions for Fran ranged from 9.0 to 10.0 meters (Figure 3C-15), and the near uniform distribution extended again from Cape Fear but covered the Top Sail Beach coastal reach before decreasing. This was also evident in the significant wave height contour plots at the peak of Bertha and Fran. The peak spectral wave periods were also elevated by 5 seconds in the Fran case, increasing both refraction effects, and depth induced breaking compared to the Bertha simulation.

d. Impact of Combined Surge and Waves. The final step and goal of the study was to estimate the impact of combined surge and waves on four sites: Topsail, Wrightsville, Kure, and Carolina Beach along the North Carolina coast. At the onset, one has to identify some of the basic uncertainties surrounding these simulations. The accuracy in the offshore topography will play a dramatic role in the estimation of nearshore wave conditions. The National Ocean Service digital database was used for constructing the final STWAVE grids, however verification of the results was virtually impossible to perform. Significant wave height estimates resulting from surge is dependent on the accuracy of the modeling technology (addressed in Paragraph 3B) and also dependent on the accuracy of the wind/pressure fields driving the model) as well as the data used to construct the area landward of the fixed shoreline.

8. Findings. Because of the complexities in this type of simulation, using a finite wave height summarizing the net effect on a particular shoreline reach is not appropriate. One has to consider the net lateral landward migration of the waves because of the surge, the gradient in wave heights in littoral zone, and to a lesser extent the offshore wave estimates. However, based on the analysis of the results derived from the coupled surge-wave simulations the following can be concluded:

a. Significant wave heights derived from Hurricane Fran were approximately 1-3m higher than during Bertha. The spatial distribution was similar.

b. The Kure-Carolina Beach domain was dominated by the largest wave conditions offshore. The gradients in wave height alongshore were uniform. Seaward the H_{mo} gradients were similar to that encountered at Wrightsville Beach, however the migration of the surge in a landward direction was significantly less.

c. The most severely impacted shoreline reach was at Wrightsville Beach because of the combined offshore wave climate, the steep offshore wave height gradients and landward migration of the wave estimates caused by surge.

d. Topsail Beach was affected by the surge slightly less than at Wrightsville Beach, and more so than at Kure-Carolina Beach. The wave climate offshore was about 1-2 meters lower than at Wrightsville and Kure-Carolina Beaches.

9. References.

Smith, J.M., Resio, D.T., Zundel, A.K. (1999). "STWAVE: Steady-state spectral wave model Report 1 User's Manual for STWAVE Version 2.0," Instruction Report CHL-99-1, US Army Corps of Engineers, Waterways Experiment Station.

Swail, V.R., and Cox, A.T. (2000). "On the use of NCEP-NCAR reanalysis surface marine wind fields *J. Atmospheric and Oceanic Technology*, Vol. 17 532-545.

Komen, G.J., Cavaleri, L., Donelan, M., Hasselmann, K., and Janssen, P.A.E.M. 1994. *Dynamics and Modeling of Ocean Waves*. Cambridge University Press, 512 pp.

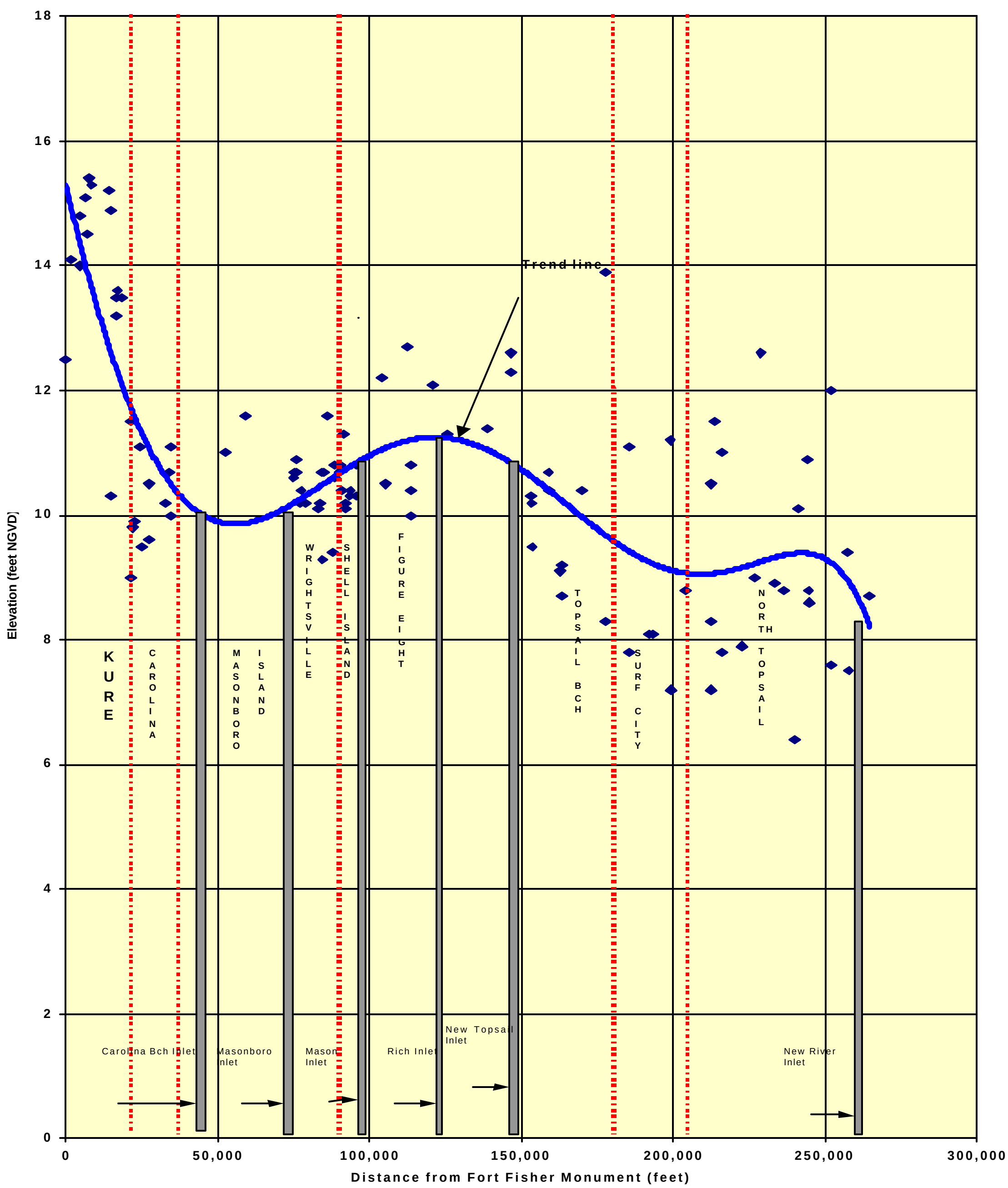
D. HIGH WATER MARKS

1. Overview. The Federal Emergency Management Agency funded a survey of high water marks left by Hurricane Fran. The survey covered the entire coastal area impacted by the storm and was conducted during September and October 1996. High water marks consisted of mud lines left on the interior of buildings or debris lines left on the ground by the receding waters. In general, the mud lines inside of buildings provide better estimates of actual storm surge and/or still water levels as the buildings tend to filter wave conditions. Debris lines, which are not affected by this type of filtering action, will include some wave runup effects, which will tend to give higher elevation readings. As shown on **Figure 3D-1**, the storm produced high water marks ranging from around 15 feet above NGVD at Kure Beach to roughly 9 feet above NGVD at the north end of Topsail Island. All observed high water marks are shown on the figure and included in the computation of the trend line in order to eliminate any bias.

2. Kure Beach. The inordinate elevation of the high water marks on Kure Beach, which are of the order of 15 feet above NGVD, are believed to be the result of local topography effects and not directly due to differing storm characteristics in the area. The location of the maximum high water marks do not agree with the post-storm numerical model hindcast of the storm surge which indicated that maximum surge and water levels should have been the highest along Wrightsville Beach. This disagreement may be the result of features that were not specifically modeled. For example, the general topography of Kure Beach is

somewhat different than the topography of the other areas in that it is really a mainland beach, with ground elevations 10 to 15 feet or more above NGVD, whereas the other areas are barrier island beaches with much lower general elevations. In addition

Figure 3D-1: High Water Marks



to the higher topography, a natural outcropping of coquina rock fronts the southern end of Kure Beach. A picture of the coquina rock outcrop is shown on **Photo 3D-1**. While the outcrop is a visible feature, this geologic formation is known to lie at or near the surface of the ocean bottom offshore of Kure Beach (see Geology, Chapter 4) and, as a result, greatly influences the slope and planform shape of the bottom contours. The presence of the rock and the high elevation of the land mass are both believed to have contributed to the higher water mark elevations in the Kure Beach area. First, the rock formation probably causes some focusing of wave energy resulting in higher waves along some section of the area, particularly in the area of the visible outcrop. Second, the high land mass could result in a partial standing wave along the area that would allow water trapped inside buildings to leave a higher water mark. Regardless of the cause, the phenomenon appears to be real, as high water marks left following Hurricane Bonnie in 1998 and Floyd in 1999 along Kure Beach were also higher than the high water mark elevations observed along neighboring beaches. Whatever, the reason, the elevation of the high water marks along Kure Beach averaged 14.0 feet above NGVD, the highest of all the areas included in the post-storm study area.

Photo 3D-1: Coquina Rock Outcrop at the Southern end of Kure Beach

3. Carolina Beach. The elevation of high water marks measured within the corporate limits of the Town of Carolina Beach following Hurricane Fran ranged from 9.0 feet NGVD to 13.5 feet NGVD. The high water marks produced by Fran were comparable to the high water marks recorded following Hurricane Hazel in 1954. Prior to Hurricane Fran, Hurricane Hazel had produced the highest still water levels of record for the Carolina Beach area. The average of all of the high water mark elevations on Carolina Beach from Hurricane Fran is 10.4 feet NGVD. The general trend of the high water marks along Carolina Beach

shows a decrease in elevation from south to north (see Figure 3D-1).

4. Wrightsville Beach. At Wrightsville Beach, Hurricane Fran produced high water marks ranging from 9.3 feet above NGVD to 11.6 feet above NGVD, with an average essentially equal to that observed at Carolina Beach of 10.4 feet NGVD. The general trend line through the high water mark data shown on Figure 3D-1 indicates a slight increase in storm still water level from Masonboro Inlet on the south to Mason Inlet on the north. The average elevation of all high water marks measured on Wrightsville Beach and Shell Island was approximately 10.5 feet above NGVD or slightly higher than the average high water marks on Topsail Island. As at Carolina Beach, the elevation of the high water marks produced by Hurricane Fran are comparable to the previously observed maximum storm still water levels in the area produced by Hurricane Hazel on October 15, 1954.

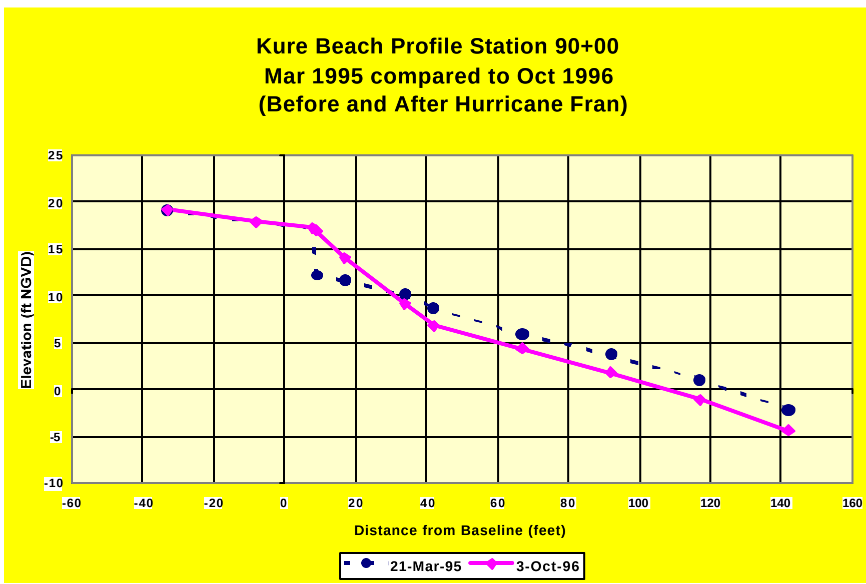
5. Topsail Island. The general trend toward lower high water mark elevations south to north along Topsail Island was due to the storm characteristics as demonstrated by the theoretical storm surge studies presented in Paragraph 3B. The straight arithmetic average of all high water marks within the various towns are as follows: Topsail Beach (10.0 feet NGVD), Surf City (8.9 feet NGVD), and North Topsail Beach (9.2 feet NGVD). No attempt was made to weight or place more reliability on any of the observed high water marks.

E. BEACH PROFILES

1. Introduction. Except for Kure Beach, the ocean beach areas impacted by Hurricane Fran consisted primarily of low barrier islands with varying dune sizes and dry beach widths fronting the dunes. The general elevation of the barrier islands landward of the dunes ranges from around 4 to 8 feet above NGVD. Kure Beach, which is actually a mainland beach, has ground elevations ranging from around 10 to 15 feet above NGVD. The difference in ground elevation between Kure Beach and the other beach areas impacted by Fran may have contributed to some of the differences in high water marks observed in the area. For the low lying barrier island, the storm surge combined with the storm waves, overtopped the beach and flowed across the islands into the bays on the back side of the islands. At Kure Beach, the high landmass prevented general overtopping and may have created a partial standing wave along the entire beachfront as water was trapped and piled up between the nearshore bar and the beach. This helps to explain why still water levels along Kure Beach were somewhat higher than the elevation of high water marks north and south of Kure Beach. This phenomenon was not unique to Hurricane Fran as similar trends in high water mark elevations (survey performed by the Federal Emergency Management Agency) were observed following Hurricane Floyd, which occurred in September 1999. Changes in beach profiles for the study area before and after Fran are shown in the following paragraphs.

2. Kure Beach. A comparison of a typical profile along Kure Beach before and after Fran is provided on **Figure 3E-1**. Station 90+00 is located 9,000 feet south of the south end of the Carolina Beach project, or at approximately the midpoint of the Kure Beach project. Due to the relatively high elevation of the landmass of Kure Beach, the upper portion of the profile was not flattened like Wrightsville Beach and Carolina Beach, rather a rather significant scarp formed along the beach front. As was the case of the other areas, there was very little if any change in the location of the 0-foot NGVD shoreline position. However, along Kure Beach, the 0-foot NGVD shoreline position was only 100 to 120 feet from the baseline. Thus the pre-storm 0-foot NGVD shoreline was 100 to 130 feet closer to the development on Kure Beach than on Wrightsville Beach and Carolina Beach. Not only was the 0-foot NGVD shoreline closer to the development, the volume of sand on the profile seaward of the baseline was considerably less than that on the two nourished beaches.

Figure 3E-1; Kure Beach Profile Station 90+00



3. Carolina Beach. Pre- and post-storm profiles for the Carolina Beach project are shown on **Figures 3E-2 to 3E-6**. The station numbering is from south to north (in feet). Station 10+00 is located 1,000 feet north of the southern terminus of the project, Station 40+00 is located near the Boardwalk area, Stations 90+00 and 100+00 are located in the northern portion of the project just south of the rubblemound revetment, and Station 125+00 is directly in front of the rubble mound revetment. The pre-storm position of the 0-foot NGVD shoreline south of the rubble mound revetment section ranged from 225 feet to 270 feet from the baseline. As is the case for Wrightsville Beach, the baseline is located along the landward crest of the artificial dune. In the vicinity of the revetment, the 0-foot NGVD shoreline position was around 100 feet from the baseline. The baseline in the revetment area is located just landward of the crest of the revetment. Changes in the profile configuration along the beach fill portion of Carolina Beach (i.e., south

of the rubble mound revetment) related to Hurricane Fran were similar to the changes observed along Wrightsville Beach, i.e., a lowering of the upper portion of the profile with very little movement of the 0-foot NGVD shoreline. The crest elevation of the dune fronting Carolina Beach had naturally increased to around 15 to 16 feet NGVD as a result of the vegetative entrapment of aeolian sand transport. In spite of this additional dune height relative to Wrightsville Beach, Hurricane Fran also generally overtopped the dune fronting Carolina Beach. The post-storm profiles south of the revetment, which were taken almost one month after Fran, include some post-storm recovery, however, the net recession of the 0-foot NGVD shoreline position was of the order of 10 to 25 feet, which again was comparable to the net recession experience at Wrightsville Beach. Station 125+00, which is located in the revetment section of the project, lost essentially all of the pre-storm dry beach area as the 0-foot NGVD shoreline had retreated to within 30 feet of the baseline.

Figures 3E-2; Carolina Beach Profile Station 10+00

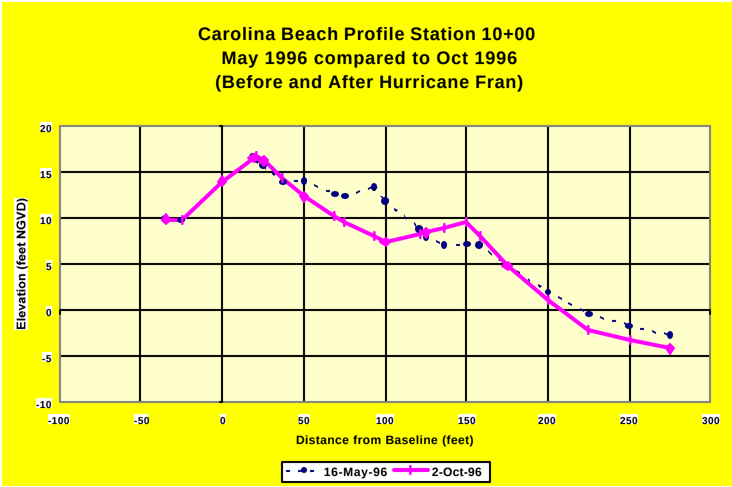


Figure 3E-3; Carolina Beach Profile Station 40+00

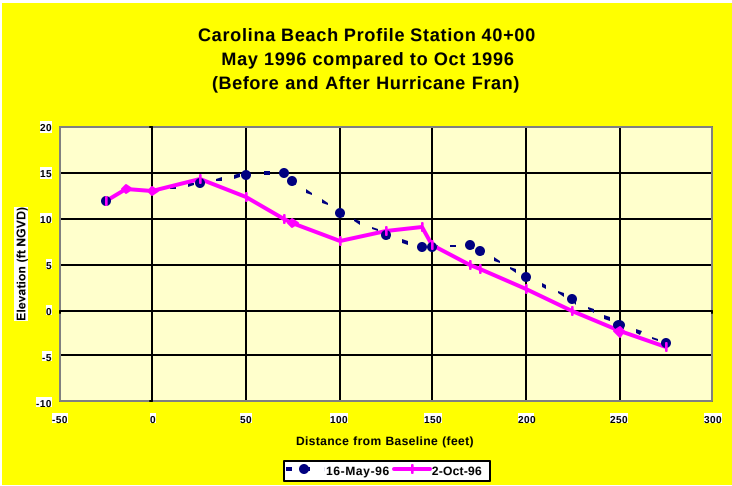


Figure 3E-4; Carolina Beach Profile Station 90+00

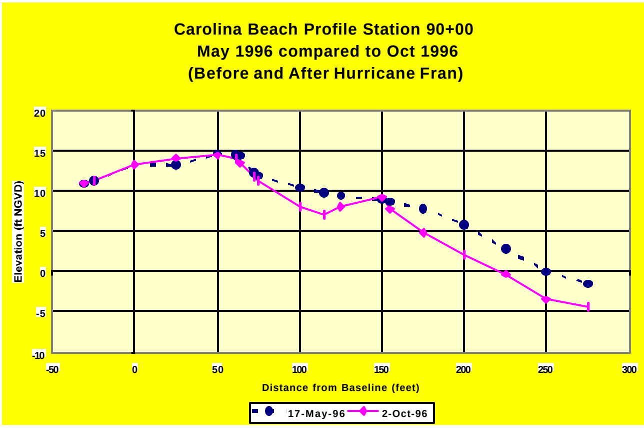


Figure 3E-5; Carolina Beach Profile Station 100+00

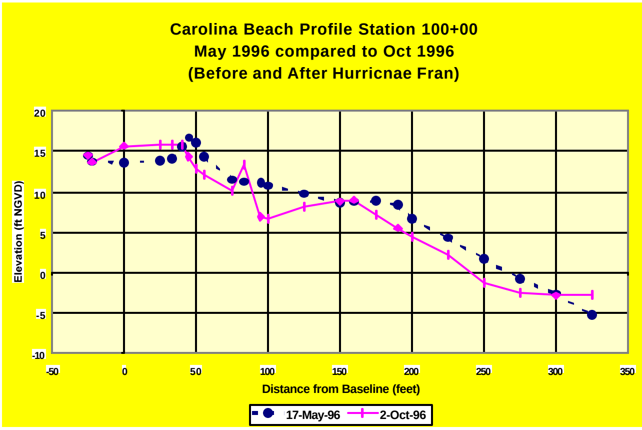
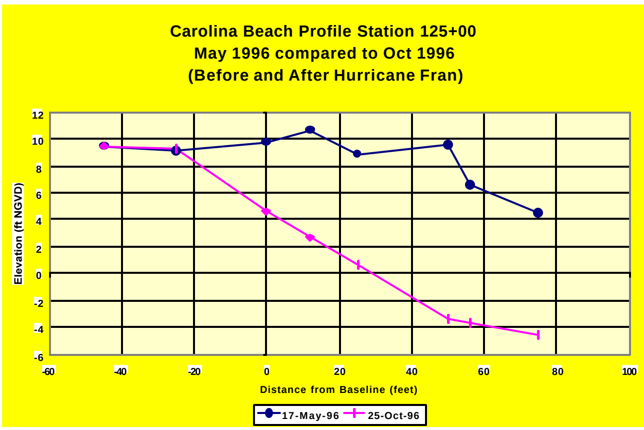


Figure 3E-6; Carolina Beach Profile Station 125+00



4. Wrightsville Beach. Beach profile surveys were taken along Wrightsville Beach in May 1996 prior to Hurricanes Bertha and Fran. Visual inspection of the beach following Hurricane Bertha did not indicate much change so the profiles were not resurveyed after that event. Hurricane Fran, on the other hand, did cause substantial reshaping of the beach profiles. Consequently, post-storm profile surveys of Wrightsville Beach were made during the latter part of September, about 3 weeks after the storm. Comparative plots of three beach cross-sections are provided on **Figures 3E-7 to 3E-9**. The station numbers for the profiles are in feet and represent the distance from the north jetty at Masonboro Inlet. Two of the three cross-sections shown (stations 100+00 and 110+00) are located south of Johnnie Mercer's fishing pier (station 119+20). Station 120+00 is located just north of the pier. All three cross-sections are in the area that has historically experienced the highest rates of erosion for the Wrightsville Beach project. The pre-project profiles indicate that the 0-foot NGVD shoreline was located between 175 and 250 feet seaward of the baseline where the baseline is located along the landward crest of the artificial dune. The major impact of Hurricane Fran on all three profiles was the flattening of the dune portion of the profiles with very little net movement of the 0-foot NGVD shoreline. In this regard, the post-storm position of the 0-foot NGVD line ranged from 150 feet to 220 feet. Also, the comparative plots show what appears to be some profile accretion above 0-foot NGVD. This apparent accretion was the result of post-storm profile recovery, which generally begin immediately upon the return of normal wave conditions.

Figure 3E-7: Wrightsville Beach Profile Station 100+00

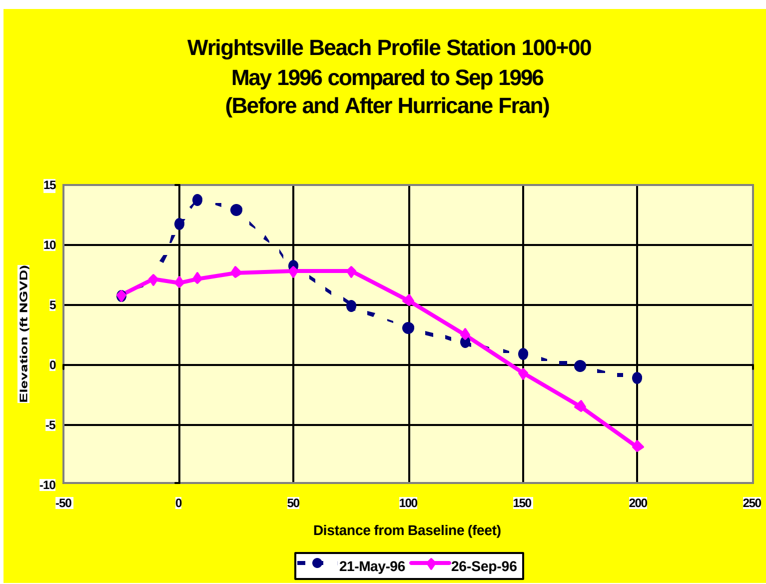


Figure 3E-8; Wrightsville Beach Profile Station 110+00

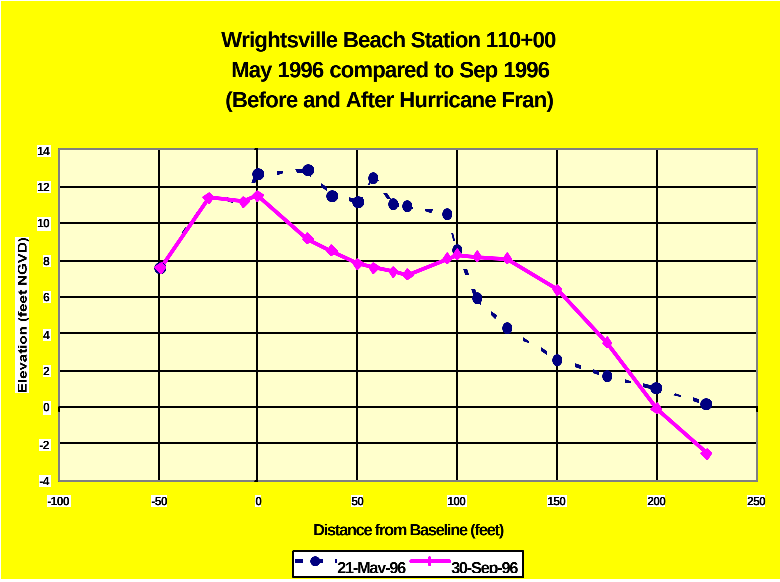
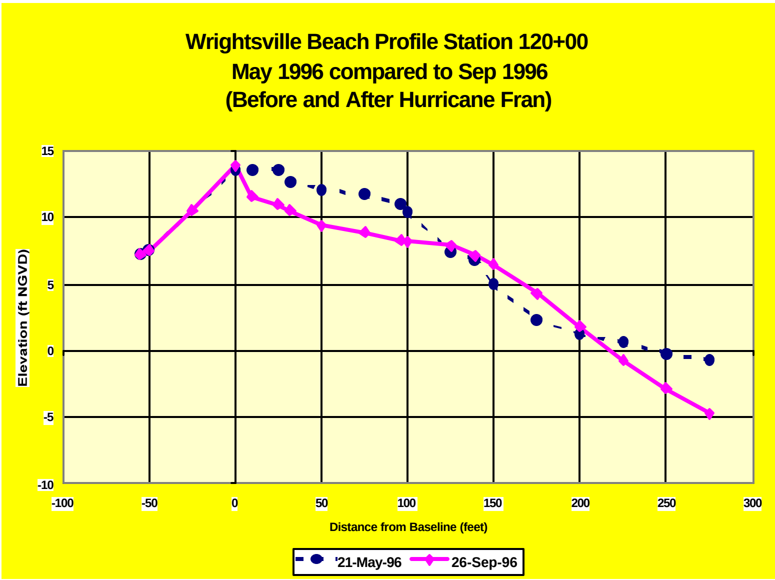


Figure 3E-9; Wrightsville Beach Profile Station 120+00



5. <u>Topsail Island</u>. Since there are no Corps shore protection projects along the coastline of Topsail Island, there are no recorded beach profiles of the area.

CHAPTER 4
GEOLOGY

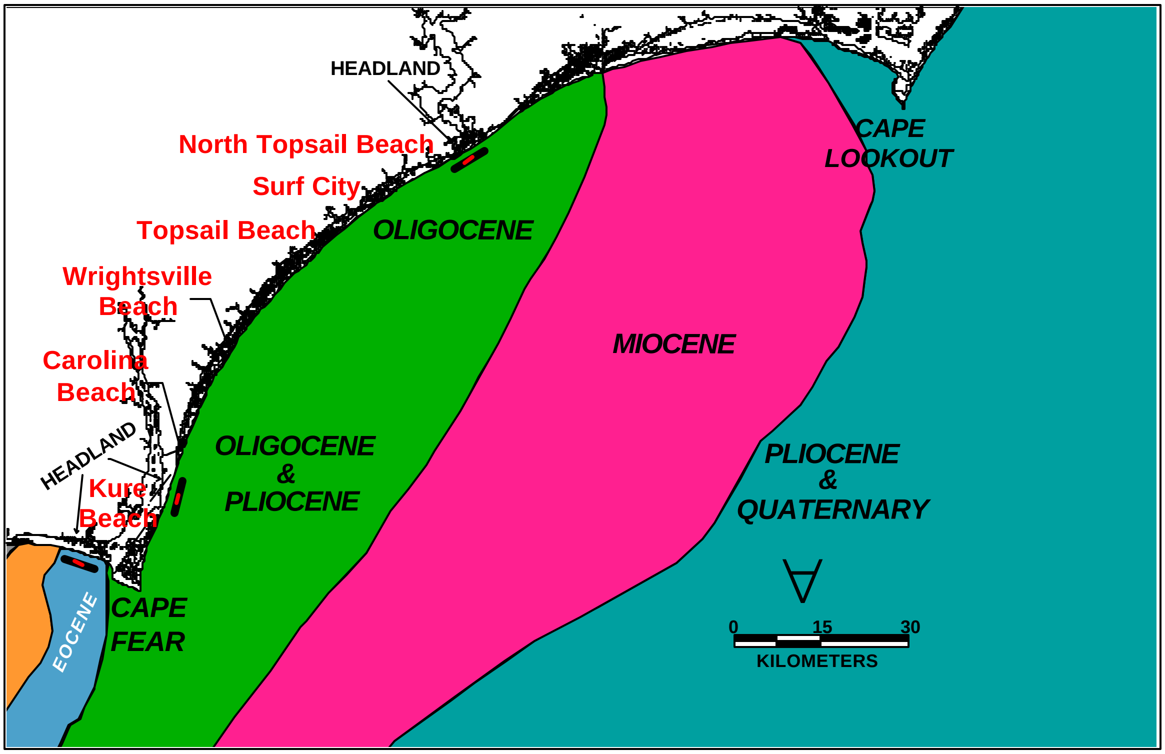
A. ROLE OF THE GEOLOGIC FRAMEWORK

1. Introduction. Data concerning the impact of Hurricanes Bertha and Fran in 1996 upon the North Carolina coastline suggests that the underlying geologic framework played a varying influential role in determining the shoreline response and subsequent beach recovery along various shoreline segments. Each shoreline reach within a 115km long impact area between Cape Fear, NC on the south and New River Inlet on the north, as well as different segments of the same shoreline reach, responded with varying degrees of susceptibility to damage and recovery. Some coastal segments (Carolina/Kure Beaches and Wrightsville Beach) have recovered through natural processes and profile manipulation; however, many severely impacted areas (much of Topsail Island) are now at an even greater risk due to the sand deficit produced by recent storms. See **Figure 4-1** for a map of the study sites and the adjacent environment. This chapter summarizes the work performed by Cleary (1999). The entire Cleary (1999) report is provided as **Appendix E** Site-specific geologic settings of the six study sites (Kure Beach, Carolina Beach, Wrightsville Beach, Topsail Beach, Surf City and North Topsail Beach) are covered. The study is approached from the perspective of how the underlying geologic framework (beneath the shorelines and shoreface) might have influenced the individual shoreline segments response to the hurricanes. Factors that are believed to have created commonalties and differences in responses are identified and the mechanisms are described and when possible supported by field data.

2. Methods and Approach. To accomplish the objectives, critical databases (i.e., seismic, sidescan, vibracore, and surface sediment, etc,) were integrated from the shoreface with data from each of the shoreline reaches. The study sites consist of both headland and barrier segments for which there are a variety of onshore and offshore data. Various levels of quality, completeness, and interpretation characterize these data. Sidescan sonar and high-resolution seismic surveys are available for the offshore portion of most of the study sites. Some of the sidescan sonar and seismic data exist in Geographic Information System (GIS) coverage that have been used to define salient morphological features and the specific nature of the shoreface. Key elements that have aided the interpretation of the remotely sensed data are extensive diver seafloor observations, and "field" maps describing the shoreface. From these data, mosaic maps of the seafloor, geologic facies maps, geologic cross sections, morphological maps of the shoreface and 3-dimentional models for some of the study sites were generated.

3. Geologic Setting. The coastwise configuration of the entire North Carolina coastline reflects major differences in the heritage derived from the underlying geologic framework. Cape Lookout separates the North Carolina coastal system into two large-scale coastal provinces. Each province has a unique geologic framework that results in distinctive types of headlands, barriers and estuaries. The study sites are located within the southern province that extends from Cape Lookout south to Sunset Beach, NC. Primarily relatively old rock units underlie the

Figure 4-1: Location Map of the Study Site with Generalized Geologic Data



region. These rocks which range in age from the Upper Cretaceous through the Pliocene are associated with Carolina Platform which underlies the region (Figure 4-1). This figure is a generalized geologic map of the continental shelf (after Snyder, 1982). Primarily Oligocene units that are often incised by channel complexes of varying age front study sites. Headland areas are also shown. Pleistocene units crop out across much of the shoreface from south of Fort Fisher to Masonboro Island. This structure platform has risen slightly causing the rocks to dip to the north and east, causing them to be truncated by the landward migrating shoreline land shoreface system (Riggs et al., 1995). Consequently, an erosional topography exists along the southern coastal province with exposures of these rock units on the shoreface. Scattered Pleistocene rock units occur in the far southern reaches of the study area particularly off the Carolina/Kure Beach headland segment. The storm impact area can be further subdivided into a series of shoreline reaches based upon different spatial orientation of the shoreline, shoreface gradient and salient bathymetric features such as shore-attached ridges and hardbottom features. These variables determine the nature of the storm and hydrodynamic settings that define the specific shoreline physiography, storm response and beach recovery.

B. SUMMARY OF SITE SPECIFIC CONTROLLING FACTORS

1. Carolina and Kure Beaches.

a. Carolina Beach is comprised of two distinct morphologic components. A barrier spit forms the northern 4.9m of shoreline. Approximately 2.7km of the southern portion of the barrier is developed. The northern 1.1km of the developed section is fronted by rip-rap. The remainder of the spit that extends to Carolina Beach inlet is undeveloped and is highly susceptible to overwash. The subaerial headland portion of Carolina Beach extends approximately 1.5km in a southerly direction to the northern limits of the Town of Kure Beach. The modern sand prism along this portion of the barrier ranges from 4.0 to 7.0m in thickness. The basal portion of the thicker sequences is comprised of isolated pockets of inland fill. The thinner sequences are located along the undeveloped spit section where lagoonal mud and peat outcrops are found along the foreshore area north of the rip-rap.

b. The Town of Kure Beach, along with the Fort Fisher enclave to the south, is located along the remainder of the subaerial headland. These headland beaches are comprised of very thin units (less than 2 to 3m) of modern sand resting on Pleistocene units of calcarenite or friable humate sandstones. Post-storm photographs clearly show the perched nature of this headland reach. While the modern beach is indeed very thin, the higher elevations associated with the old headland topography probably helped reduce the impacts of the elevated water levels and associated overwash.

c. The majority of overwash and severe structural damage that occurred along Carolina Beach was restricted to the northern portion of the developed section in the vicinity of the rip-rap. This chronic erosion zone has historically been subject to frequent overtopping during storms since the emplacement of the rip-rap in the late 1960's and early 1970's. Erosion of the artificial dune and berm did occur along the remainder of the Carolina Beach oceanfront to the south but overwash and structural damage was very minimal. Overwash was restricted to the dune walk-overs and along the low, flood-prone section near Carolina Lake, a turn of the century inlet zone.

d. Moderate storm damage and overwash occurred along the topographically higher Kure Beach oceanfront. Shoreline recession damage to the oceanfront homes was related to the lack of a wide beach and dune system. Because the backshore area is topographically high, overwash and structural damage was restricted to the oceanfront.

e. The complex bathymetry of the shoreface off this headland influenced shoreline segment stems from the development of the large relict northeast trending shore attached ridges on top of the hardbottoms of varying lithology and relief. Although hardbottoms are widely distributed across this headland shoreface, scarps appear to be more numerous and of higher relief along the southern portion of the headland off the Kure Beach upper shoreface. The higher relief and more frequent scarps in the southern portion of area probably played a minor role in the initial impact of the storm. The degree of recovery that might have taken place was masked by the artificial manipulation of the beach profile. The amount of recovery that would have occurred in this reach is open to question. It is likely that forebeach buildup would have taken place but it would have been limited due to the complex offshore bathymetry.

f. Along Carolina Beach, natural recovery was probably limited to forebeach accretion involving material returned to the beach from the offshore area down to depths of approximately 8m. The pre-storm condition of this entire shoreline reach coupled with the convoluted nature of the upper shoreface and the morphology of the hardbottoms, must have impacted the surge elevations and dictated transport pathways across the uplands and shoreface.

g. Much of the sediment cover in this area is derived from the degradation of the coquina hardbottoms and the reworking of the paleo-channels that are incised into the bedrock. Although this shoreface generally has more sediment cover than North Topsail Beach or Surf City, long-term natural recovery of the shoreline is highly unlikely given its erosion history and the complex nature of the shoreface.

2. Wrightsville Beach.

a. Wrightsville Beach is a 7.3km long barrier island composed of two former barrier segments. Data show the entire barrier is underlain by inlet fill deposited during the past several hundred years. As a result, the barrier platform is relatively thick in comparison to the modern beach on the headland influenced shoreline segments. In this area, modern sand sequences are up to 10m thick. Beneath the basal inlet sequence are early Holocene lagoonal muds, compact Pleistocene muds and older limestone units.

b. The majority of the significant overwash and the limited structural damage occurred within the chronic erosion zone that developed along the mid barrier shoreline bulge. Other sections of Wrightsville Beach, located south of Mercer's Pier and the shoreline bulge, were impacted only slightly. Much of the remaining portions of Wrightsville Beach south of old Moore's Inlet has been frequently renourished. As a result, much of the barrier was characterized by a relatively wide artificial beach/dune system during the summer of 1996. Overwash and erosion was limited along almost the entire southern section of the beach. Similarly, along the shoreline reach north of old Moore's Inlet, dune erosion occurred but for the most part overwash was restricted to the breaks within the foredune and within the dune swales. Little structural damage occurred along the northern part of Wrightsville Beach (Shell Island).

c. The numerous shore-normal rippled scour depressions that are characteristic of the shoreface off Wrightsville Beach and the scattered hardbottom areas in all likelihood did not play a significant role in determining the impact of the 1996 hurricanes on the Wrightsville Beach shoreline. However, the coastwise shape of the shoreline coupled with cross-shore morphology may have been responsible for the seaward transport and loss of an unknown volume of beach material during the storms. The cumulative effect of this asymmetric cross-shore flux lead to a historical sediment deficit that translated into net shoreline retreat. The large volume of beachfill frequently placed along the shoreline during the past four decades helped to offset the above-mentioned loss.

d. Historic aerial photographs of Wrightsville Beach dating from the late 1920's and early 1930's clearly show numerous groin and bulkheads indicating that erosion was rampant along the entire barrier. The island was exceptionally narrow with a poorly defined foredune. It is surprising that Hurricane Hazel in October 1954 (a category 2 storm) did not cause more damage when one considers the poor condition of Wrightsville Beach at that time. Aerial photographs suggest that North Topsail Beach had a healthier beach/dune system in the early 1980's than Wrightsville Beach did before the landfall of Hurricane Hazel in 1954. *Without the extensive restoration that has occurred since the mid 1960's, the impact of Hurricane Fran on Wrightsville Beach would have been extreme, and likely worst than the damage recorded along Surf City and North Topsail Beach.*

3. Topsail Beach.

a. Topsail Beach comprises the southernmost 7.2km of Topsail Island. The southern 11km segment of Topsail Island is a variable relief spit that has extended to the south during the migration of New Topsail Inlet over the past 300 years. The barrier platform's sand prism is relatively thick consisting of and 8-11m sequence comprised of inlet fill, beach, washover and dune sediments. The southern 2km section of this shoreline reach has been a chronic erosion zone and the site of extensive overtopping during recent storms. The erosion stems from the realignment of the shoreline (Topsail Beach) as the inlet migrated to the southwest. The attendant planform changes have led to dramatic changes over the past 20 years.

b. As a result of the inlet's influence on the updrift barrier planform, small-scale replenishment projects that have been undertaken have had little chance of success in mitigating the erosion. Although a small artificial dune and berm was in-place during the summer of 1996, it did little in the way of mitigation storm-related erosion and extensive overwash. The morphologic changes and structural damages that did occur are related more to the pre-storm condition of the barrier than to the geologic controls.

c. The shoreface off Topsail Beach is similar to the area off Surf City. Much of the nearshore area, out to depths of 10-14m, consists of Oligocene limestone and siltstone hardbottoms with a thin (less than 1.0m) veneer of silt and fine sand. The shoreface morphology is generally flat with occasional 1.0m scarps. It is unlikely that this type of shoreface geometry played a significant role in the storm's impact on the adjacent beach.

4. Surf City.

a. Surf City, occupying the central portion of Topsail Island, was one of the most severely impacted shoreline reaches within the impact area. The low-lying barrier in this area fronts an extensive 200 year-old vegetated flood tidal delta. The pre-storm beach was characterized by low relief, scarped and often discontinuous, foredunes. The sand prism that comprises this section of the barrier is relatively thick (8-10M). The lower portion of the barrier platform along much of this area overlies a sequence of inlet fill associated with Stumpy Inlet and pre-historic inlets. Lagoonal mud and peat underlie the northern and southern extremities of Surf City.

b. It is interesting to note that the worst damage and overwash occurred along the shoreline stretch that fronted the most recent position of the wide and ephemeral Stumpy Inlet. The 4.5km long barrier shoreline segment south of the old inlet, as well as portions of the shoreline north of Surf City, were the site of the only minor overtopping, although dune erosion did occur. These aforementioned areas, where overwash was confined to topographically higher oceanfront areas, may represent the former inlet's shoulders where larger, wider and older dune fields are present. One can speculate that the closure of the old inlet led to planform (island curvature) changes. Following the closure of the former breach this area did not develop a significant dune field due to a lack of a suitable sediment source.

c. The erosion history over the past decade has resulted in a narrowing on the foredune along the former inlet zone. Furthermore, development in the area has lead to the removal and alteration of the character of the low relief backbarrier dune field, which has increased the hazard potential.

d. It is unlikely that the geology of the shoreface had a significant effect on the storm's impact in this area. The offshore area beyond depths of 8-9 m is characterized by extensive low relief hardbottoms mantled by a patch veneer of fine sand of variable thickness. The Oligocene limestone that is exposed across the shoreface is extremely indurated and is not a major contributor of new sediment to the overlying modern sediment cover in the long-term. However, some contributions from the hardbottoms were evident along the post-storm beach that was littered with extensive coarse sand and limestone clasts derived from the immediate offshore area.

e. No detailed morphologic information about the shoreface morphology exists for this area. Fathometer profiles indicate that occasional low relief landward facing scarps and flat hardbottoms mark the shoreface off Surf City, seaward of 8-9m water depth. The exact role the geologic framework played in the storm's impact on this shoreline segment and the subsequent beach recovery is difficult to determine.

5. North Topsail Beach.

a. North Topsail Beach comprises the northern 18.7km of Topsail Island. Much of this barrier segment is influenced by the New River submarine headland and as a result the modern barrier sand prism is relatively thin (less than 2.0m). The barrier is perched on top of a variety of older materials including peat, lagoonal mud and compact Pleisocene mud. The extensive outcrops of peat and cedar stumps along much of the central portion of this shoreline segment testify to the very low volume of material comprising the barrier platform.

b. Cores, aerial photographic data and vegetation patterns indicate the majority of this shoreline reach has been a chronic washover zone for the past several centuries. The high susceptibility to repeated overtopping suggests the vulnerability of this area is related to a lack of significant recovery between events. The 1996 pre-storm condition of the beach played a direct role in the severity of the damage and the extensive erosion recorded along North topsail Beach. The pre-storm condition was related to the scarcity of sand in the hardbottom dominated nearshore system.

c. The factors that were instrumental in the long and short-term erosion and morphologic development of much of the northern section of Topsail Island can be related to the geologic nature of the shoreface. The morphologic expression of the submarine headland in the form of extensive moderate relief hardbottoms probably played a significant role in both the storm's impact and the shoreline recovery over the short and long-term. The regional limestone platform-like feature along with the localized bathymetric highs (scarps) must have influenced the incident waves and storm-generated currents along and across the shoreface. Over the recent geologic past these features have played a significant role in the morphology of Late Holocene as well as modern barriers in this area of Onslow Bay.

d. The geometry and composition of the hardbottoms has also affected the recovery of the shoreline, not only after the storms of 1996, but previously events as well. The irregular karstic surface that comprises the shoreface is composed of a series of irregularly space, landward facing scarps and intervening plateaus or depressions. The northern portion of the shoreface north of Alligator Bay has more numerous and higher relief scarps. This segment of the shoreface has little or no sediment cover and lies adjacent to the shoreline reaches that experienced the greatest damage and the most severe erosion and overwash. The bathymetry of the central and northern portion of the shoreface off North Topsail Beach shows several shore normal topographic lows that extend across much of the shoreface. These linear channel-like features are constrained by topographically high hardbottoms and may represent solution features that have been modified by fluvial processes during low lands of sea level. Regardless of origin, they appear to act as conduits for cross-shore transport of material to the inner-shelf. A mosaic of migrating ripple fields covers the graded storm sequence recovered from beneath these conduits. The loss of sediment via these channel-like areas and the trapping ability of the numerous irregularly spaced scarps precludes shoreline recovery along this area.

e. The durability and quartz-poor nature of the limestone units that form the extensive outcrops does not lend itself to the production of large volumes of new sand-sized sediment by shoreface processes. The orientation of the shoreline and the frequent storms that impact this sediment-starved shelf sector have combined to produce a barrier segment that is poised to migrate rapidly. The rollover is directly related to the storm history and the geologic nature of this morphologically unique shoreface.

C. THE GEOLOGIC FRAMEWORK AND THE SHOREFACE PROFILE

1. Value of the Shoreface.

a. The shoreface is the link that couples the shoreline and the inner shelf. This complex environment can act as a source, barrier or avenue for bi-directional transport of materials between the beach and the deeper offshore areas. The geologic and oceanographic processes operating across this environment play a variable role in determining how a shoreline reach will respond to individual storms and the collective impact of storms over the long term.

b. The shoreface has traditionally been thought of to be sand rich and achieve an equilibrium shape relative to wave climate and surficial sediment grain size (Bruun, 1954; Dean, 1977 and Zeider, 1982). Bruun (1954 and 1962) first proposed an equilibrium profile equation. Bruun (1962) used this equation to develop a simplistic model for coastal evolution, in which a constant profile shape translates landward and upward in response to sea-level rise. Dean (1977 and 1987) later focused on the importance of grain size in describing shoreface response and evolution. The concept of an equilibrium profile relies on several important assumptions about the nature of the shoreface and processes that are not consistent with most shoreface systems (Pilkey et al., 1993 and Thieler et al., 1995). The concept has been accepted as valid and is a fundamental principle behind most analytical and numerical models of shoreline change used to predict shoreface/shoreline behavior (e.g., Hansen and Lilycrop, 1988; Hanson and Kraus, 1989 [the GENESIS model] and Larson and Kraus, 1989).

2. Geologic Framework.

a. The complex geology of the six sites, particularly the headland shorefaces, does not lend itself to the application of equilibrium profile-based models. In addition to the fact that most shorefaces are dominated by patchy hardbottoms of varying relief, there is a lack of a consistent grain size across the profile and therefore grain size variations are too complex to be described by simple equations and parameters. It is not uncommon for the grain size to vary from silt to boulders within a distance of several meters in the vicinity of hardbottoms.

b. In southeastern North Carolina, the geologic framework is the predominant control on shoreface profile shape. On these shorefaces, the stratigraphic framework controls outcrop patterns, hardbottom distribution, bathymetry, and ultimately sediment characteristics. The shapes of these bedrock-controlled shorefaces are further complicated off the headland reaches by the relict ridges and karst topography inherited from previous lower stands of sea level. The resulting bathymetric signature is not characterized by shore-parallel isobaths, and therefore, does not lend itself to numerical modeling.

c. During individual storm events, cross-shore transport of sediment on these hardbottom dominated shorefaces is more complex than would be envisioned by simple shoreface equilibrium models. Although the influence of the hardbottoms on cross-shore transport is yet to be determined, one can speculate that in areas where sediment cover is very thin and hardbottom relief is relatively high, their impact on the benthic boundary layer structure and bed shear stress must be substantial.

d. Off North Topsail Beach, the bottom morphology and bed roughness related to the irregular spacing and relief of the scarps, coupled with the patchy nature of the corrugated, flat, algal-encrusted hardbottoms, dictated the ultimate shoreline erosion patterns and the direction and volume of sediment transport. Along the intra-headland barrier segments of Surf City, Topsail Beach and Wrightsville Beach the role of the underlying geologic framework was minimal. In a relative sense the shoreface geology off the headland segment at Carolina-Kure Beach, characterized by numerous low relief ledges, flat hardbottoms, and large shore-attached ridges, played a moderate role in dictating the observed erosion and recovery patterns.

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CHAPTER 5
ECONOMIC DAMAGE ASSESSMENT

A. INTRODUCTION

1. Overview. An analysis of economic damages was conducted on three islands encompassing six North Carolina towns (Kure Beach, Carolina Beach, Wrightsville Beach, Topsail Beach, Surf City, and North Topsail Beach). Both Carolina Beach and Wrightsville Beach have had Corps of Engineers shore protection projects in place for approximately 30 years. The other communities did not have shore protection projects at the time of Hurricane Fran in September 1996. Demographics for the study area were also collected. The sources of this data were Wilmington District, U.S. Army Corps of Engineers (Corps); Federal Emergency Management Agency (FEMA); local town and county managers; and building inspectors.

2. Economic Evaluation Process.

a. Report Evaluation. In this report, Federal Insurance Administration (FIA) claims data were used as an indicator of actual damages to structures and personal property. These claims were compared in the areas that had a shore protection project to those areas that did not when Hurricane Fran struck on 5-6 September, 1996. This is different from a typical Corps planning report that calculates a benefit-cost ratio and maximum net benefits. "Benefits" of the existing shore protection projects, per se, were not calculated in this particular study; nor were "damages prevented." Both of these measures involve measuring hypothetical situations as described below.

b. Traditional Benefit Evaluation. The Corps traditionally calculates benefits in the planning phase of a project. The "without project" existing conditions are compared to hypothetically modeled "with project" conditions. Neither situation can be measured directly, because both the without and the with project conditions are protected into the future, usually for a period of 50 years.

c. Damages Prevented Evaluation. The Corps also often calculates "damages prevented" when a project has been built and a storm has hit the area. Models are run to estimate damages with the project in place (and calibrated to actual storm data) compared to the hypothetical situation of what the damages would have been if the project was not in place.

B. DEMOGRAPHICS

1. Introduction. The Greater Wilmington area, which encompasses a significant portion of the report study area, has been and still is one of the fastest growing areas in the country. Because of this, the 1990 Census demographic information gives us only a partial picture of the demographics of the area. At the time of the collection of the data for this report, the counties of New Hanover, Pender and Onslow were in the process

of automating their data. Current data, therefore, were often limited. Caution must also be taken when using 1990 census information, particularly with measures of economic activity. Information on the counties as a whole is given for comparative purposes to highlight the differences in demographics between the counties and the beachfront communities in those counties.

2. Land Area and Incorporation. Significant portions of the counties being examined are unincorporated, though incorporation continues. Incorporated towns and cities in the study area have jurisdiction over some of these unincorporated areas. This is the case with the small areas of Hanby Beach and parts of Wilmington Beach, which fall under Kure Beach's jurisdiction. The remainder of Wilmington Beach is under Carolina Beach's jurisdiction. Surf City just annexed the Onslow County portion of Surf City in 1988, and has had a small amount of unincorporated mainland area under its jurisdiction since 1992. Prior to 1990, North Topsail Beach was an unincorporated part of Onslow County, known as West Onslow Beach. Because North Topsail Beach was incorporated right after the 1990 census was conducted, a limited, special census had to be undertaken. This ongoing process of recent incorporation and extra-jurisdictional territory makes the measurement of demographics even more challenging. Land area and incorporation dates are summarized in **Table 5-1**. Throughout this chapter, the demographics and damages associated with Wrightsville Beach are for the entire incorporated area of town of Wrightsville Beach. This area includes not only the 14,000-foot long ocean front Corps project (from Masonboro Inlet north to approximately Moores Inlet Street) but also includes the northern part of Wrightsville Island (Shell Island), Harbor Island and mainland Wrightsville Beach (see Photo 2-4 and Figure 2-4).

Table 5-1: Land Area and Incorporation Date

Area	Land Area (sq. mi.)	Year Chartered
New Hanover County	199	1759
• Kure Beach	0.8	1947
• Carolina Beach	1.7	1925
• Wrightsville Beach	1.3	1899
Pender County	871	1875
• Topsail Beach	5.0	1963
• Surf City	4.7	1949
Onslow County	767	1734
• Surf City	0.5	1998
• North Topsail Beach	14.7	1990

3. Population.

a. Introduction. While the entire study area being examined has experienced tremendous growth in the 1990s, most of the beach communities have experienced growth equal to or greater than that of the surrounding county. The exception to this is Wrightsville Beach. This is because Wrightsville Beach has been an established beach resort community throughout the 20th century and had little remaining undeveloped land even by 1980. Many of the single-family homes are summer homes and have been in the family for years.

b. Statistics. Census statistics for population and economic activity of these beach communities are greatly understated as the census only takes into account permanent residents of the area. In addition to permanent residents, there are two categories of seasonal populations; they are "summer population" and "day trippers". Summer population includes those on overnight to extended stays in both rental houses and motels. Day trippers are defined as visitors from the local area. Seasonal populations in this area can soar to over ten times the permanent population. Seasonal population is estimated in the land use plans produced under regulation by the North Carolina Coastal Area Management Act (CAMA).

c. Specifics. New Hanover County, the smallest but most densely developed county, contains the city of Wilmington (population 62,968) and the towns of Kure Beach, Carolina Beach and Wrightsville Beach. The remainder of the county is unincorporated. Pender County, abutting New Hanover County on the north, is thought of as a bedroom suburb of Wilmington and has experienced the greatest growth of the three counties in the study area because of the availability of undeveloped property. It is the largest of the three counties and the least densely populated. Most of the county is unincorporated with the exception of a few small towns, the largest being the county seat of Burgaw (population 3,519). Onslow County, adjacent to Pender County on the north, contains the city of Jacksonville, which experienced 149 percent growth in population from 1990 to 1996. Jacksonville is the county seat and has a population of 75,527. Onslow County also contains a few small towns and the Camp Lejeune Marine Corps Base. The summary of this population data and the drastic increases in summer population are contained in **Table 5-2**.

Table 5-2: Population

Area	1980	1990	1980-1990 change	1996	1990-1996 change	1996 Density (person/ sq. mi.)	Summer Population/ Day trippers
New Hanover County	102,779	120,284	17%	143,430	19%	721	n/a
• Kure Beach	611	619	1%	738	19%	923	7,000/ 2,000
• Carolina Beach	2,000	3,630	82%	4,690	29%	2,759	13,000/ 25,000
• Wrightsville Beach	2,789	2,937	5%	3,165	8%	2,435	10,000/ 35,000
Pender County	22,262	28,855	30%	35,978	25%	41	n/a
• Topsail Beach	220	346	57%	434	25%	87	7,000/ 1,000
• Surf City	390	653	67%	810	24%	172	9,000/ n/a
Onslow County	112,784	149,838	33%	150,216	0%	196	n/a
• Surf City	n/a	317	n/a	337	6%	674	Included in Pender Co.
• North Topsail Beach	n/a	947	n/a	1,091	15%	74	14,000/ 3,000

n/a = not available
Sources: 1980 and 1990 U.S. Census; N.C. Office of State Planning; CAMA Land Use Plans

4. Housing. The study area has a wide variety of housing including both single family and multiple occupancy, ranging from smaller traditional beach cottages and mobile homes to luxury homes and high rises. Prices range from less than $100,000 to millions of dollars. Wrightsville Beach is the most affluent of the six communities in our study area and is the closest geographically to a major city (Wilmington). Because the greater Wilmington area is experiencing tremendous growth, housing prices throughout the study area continue to escalate, driven by demand, though differing county to county. Median house values from the 1990 U.S. Census for the communities are grossly underestimated compared to 1996 values. Values have increased 200 to 300 percent since the 1990 Census. Summarized in **Table 5-3** are the housing statistics and tax rates. Note that town tax rates shown in the table are in addition to the county tax rate.

> "From 1994 to 1995, local realtors estimated that housing costs jumped as much as 14 percent on average with an increase of as much as 20 to even 40 percent in upscale beach communities." (p. 349, *The Insiders' Guide to Wilmington & North Carolina's Southern Coast).*

Table 5-3: Housing Statistics

Area	Housing Units (1990)	Units Owner Occupied	Units Renter Occupied	Units Vacant a/	%SF: %MF: %Other b/	Median Value (1990) c/	1996-97 Tax Rate/ $1000
New Hanover County	57,076	30,193	17,946	8,937	63:28:9	$72,000	0.645
• Kure Beach	937	173	109	655	56:40:4	$81,300	0.39
• Carolina Beach	3,342	801	804	1,737	38:61:1	$80,100	0.40
• Wrightsville Beach	2,413	715	686	1,012	46:51:3	$192,700	0.235
Pender County	15,437	9,182	1,930	4,325	61:6:33	$60,200	0.65
• Topsail Beach	998	136	43	819	79:21:0	$149,000	0.27
(Pender/Onslow) • Surf City	2,242	306	188	1,748	44:18:38	$98,900	0.45
Onslow County	47,526	21,835	18,823	6,868	61:13:26	$62,200	0.644
• North Topsail Beach	2,173	n/a	n/a	n/a	n/a	n/a	0.29

a/ Including seasonal dwellings b/ Mobile homes, boats, etc. c/ Owner-Occupied
n/a = not available
Sources: U.S. Census

C. DAMAGES

1. Overview. An economic damage assessment to ascertain storm effects at the areas that were not protected by Corps projects (Kure Beach and Topsail Island) in comparison with those that were protected by Corps projects (Carolina Beach and Wrightsville Beach) for Hurricane Fran was performed. The primary focus was on the comparative analysis between protected and unprotected areas rather than an absolute quantitative analysis. Comparison of damages was done by examining total damage based on FIA claims in the communities compared to the communities' total property bases. Damages were further analyzed to compare differences in oceanfront properties for those communities protected by Corps shore protection projects to those not protected.

> "Expect to pay an average of $500,000 for virtually any single-family home [in Wrightsville Beach] and don't be surprised by much higher prices, since the available land is all but exhausted in terms of development on the island...Homes can be purchased for as low as $80,000 and can rise to a half-million dollars along Carolina Beach, Wilmington Beach, Kure Beach and Fort Fisher...Unlike the decidedly pricier beaches to the south, Topsail Island offers homes for $100,000 or less in some cases. New 2,000-square-foot homes can cost as much as $250,000 to $300,000 on the ocean, although there are not yet many homes this large on the island. The norm is more 1,500 to 1,800 square feet, and prices average $175,000 to $200,000" (p. 358-360, *The Insiders' Guide to Wilmington & North Carolina's Southern Coast*).

2. Information Source. FIA claims were the primary source of damage data. Other sources were interviews with local community officials, FEMA Damage Survey Reports and *Building Performance Assessment* report, and CAMA land use plans. FIA claims are useful when evaluating damages due to the absence or presence of a shoreline protection project because flood insurance covers damage caused by storm surge, wave wash, tidal waves or overflow of any body of water from above-normal cyclical levels. FIA flood insurance does not cover property damage caused by wind-driven rain entering your home or business through openings in the roof or walls. Rainwater and wind damage from a roof, window or wall opening would, in most cases, be covered by standard homeowners' policies. Because of this exclusion of wind and rain damage from flood insurance policies, this study does not overestimate damages that could be prevented by a shoreline protection project. A building and its contents are treated separately so either or both can be insured. For residential buildings, coverage of up to $250,000 is available; up to $100,000 is available for contents. Coverage for nonresidential structures and separate coverage for contents are available up to $500,000 each.

3. Damages by Community.

a. Kure Beach. Structural damage to development along the oceanfront of Kure Beach was extensive, as no structure escaped damage and several were totally destroyed. **Photos 5-1 to 5-4** provide graphic visuals of the type and extent of damage in Kure Beach. Close examination of Photo 5-2 shows a completely denuded beach with exposure of old marsh and peat deposits that are exposed on the beach surface. Photo 5-3 was taken in the vicinity of the Kure Beach Pier and shows damage to a timber bulkhead and complete destruction of a parking lot located immediately behind the bulkhead. Photo 5-4 is an aerial shot showing at least three buildings that appear to have been totally destroyed.

Photos 5-1, -2, -3, -4; Kure Beach after Fran

b. Carolina Beach. Structural damage behind the beach fill portion of the protection project fronting Carolina Beach was limited to that caused by wind, rain, and flooding from the sound side. Also, some floodwaters entered the town from the north around the north end of the rubble revetment as well as wave overtopping of the revetment. While the storm surge elevation combined with the accompanying storm waves generally overtopped the dune, the only significant impact of this was the deposition of sand inside the lower floors of ocean front buildings and along the road paralleling the ocean. There was essentially no wave impact damage. Not only did the ocean front structures escape serious damage; the dune walkover structures were not damaged. **Photos 5-5 and 5-6** show the typical condition of Carolina Beach following Hurricane Fran. In Photo 5-5, which was taken in the vicinity of the Boardwalk business area, dune overtopping is evidenced by sand ripples in the dune. In spite of this overtopping, the dune

Photos 5-5 and 5-6; Carolina Beach after Fran

walkover structures are still intact. On Photo 5-6, which was taken north of the Boardwalk area, there is an obvious absence of significant damage to the dune, the dune grass, and the ocean front structures. The only significant damage to ocean front structures in Carolina Beach occurred to several buildings located behind the rubblemound revetment that covers the northern 4,000 feet of the project. Some of the damage occurred to older structures that did not meet current first floor elevation requirements while others appeared to be damaged by floating piles and other debris that were carried shoreward from the fishing pier that was completely destroyed by the storm.

c. Wrightsville Beach. The storm damage reduction project, with its dune at elevation 13.5 feet above NGVD, was generally overtopped along its entire length north of the Oceanic Pier (located approximately 3,200 feet north of Masonboro Inlet). In addition to being overtopped, as shown by the profile comparisons (see Chapter 3 Section E), a considerable amount of dune erosion also occurred north of the Oceanic Pier. Even though the dune was eroded and generally overtopped, none of the ocean front development received any substantial damage due to wave impacts or storm surge. This lack of wave or surge related damage was attributed to the width of the beach above NGVD that existed prior to the storm. Post-storm photos of Wrightsville Beach are shown on **Photos 5-7 to 5-9**. Photo 5-7 was taken just north of the Islander Condominium and is looking south toward Mercer's pier. As shown by the profile comparisons, Hurricane Fran generally destroyed most of the dune over the northern half of the project area but again caused no significant damage to ocean front buildings. Photo 5-8 was taken looking south toward Masonboro Inlet. This particular area is within the accretion fillet of the Masonboro Inlet north jetty and is characterized by a wide beach and substantial dune system. The fillet area was not overtopped during Hurricane Fran. Photo 5-9 is an example of the type of damage experienced along Wrightsville Beach, which for the most part, was due to wind, rain, and elevated sound waters. The house shown on Photo 5-9 is located just south of Johnnie Mercer's pier in the vicinity of baseline station 110+00.

Photos 5-7, -8, and –9; Wrightsville Beach after Fran

Photo 5-7
View looking south toward Mercers Pier

Photo 5-8
View looking south toward Masonboro Inlet

Photo 5-9
Wrightsville Beach after Hurricane Fran showing wind damage to ocean front structure

d. Topsail Island.

(1). Damages. Prior to Hurricane Fran, most of Topsail Island was fronted by a vegetated natural dune with the exception of the southern 2-miles, which had a small man-made dune formed by scraping sand off the beach, and portions of North Topsail Beach, which also was protected by a man-made dune. Even though a dune did exist along most of the island, there was very little dry beach fronting the dune during normal high tide. Hurricane Bertha, which hit the area in mind July 1996, severely weakened the dunes. Hurricane Fran, which occurred eight weeks later, completed the job, destroying all of the man-made dunes along Topsail Beach and North Topsail Beach. Hurricane Fran also destroyed most of the natural dunes with the exception of approximately 2.5-miles of shoreline in the Town of Surf City where the landward portions of the dunes still remain. Hurricane Fran caused extensive erosion of the shoreline, rendering a majority of the ocean front lots unbuildable and caused extensive structural damage to ocean front structures as well as structures located on the second and third rows from the ocean. Examples of the types of damage experienced along Topsail Island are shown on **Photos 5-10** for the Town of Topsail Beach, **5-11 and 5-12** for the Town of Surf City, and **Photos 5-13 to 5-16** for the Town of North Topsail Beach.

Photo 5-10; Town of Topsail Beach after Fran

Photo 5-11; Town of Surf City after Fran

Photo 5-12; Town of Surf City after Fran

Photos 5-13 through 5-16; Town of North Topsail Beach after Fran

(2). Island Breaches. In addition to the damage to the dune and beach system, Hurricane Fran breached the island in approximately five locations, resulting in the creation of temporary inlets. Emergency work performed by the North Carolina Department of Transportation and the natural recovery of the beach resulted in closure of four of the breaches within a few weeks following the storm. However, the fifth breach, which was located approximately 2-miles south of New River Inlet, remained open for almost a year following Hurricane Fran. **Photo 5-17 and 5-18** show two of the smaller breaches that occurred along North Topsail Beach. **Photo 5-19** shows the northernmost and largest breach. All three photos of the island breaches were made within a few days following the storm. Several of the breaches along North Topsail Beach, including the northernmost breach shown on Photo NTB-7, occurred in low areas which had been bridged to prevent damage to wetlands when the highway was relocated landward in the 1980's. The longevity of the northernmost breach is testament to the scarcity of sand in the littoral system of Topsail Island as discussed in the Geology Chapter (Chapter 4).

Photo 5-17, -18 and -19; Breaches at North Topsail Beach following Fran


Photo 5-17


Photo 5-18


Photo 5-19

4. Damage Comparison.

a. Percent Damaged. Kure Beach and Topsail Island, both unprotected areas, sustained a greater percentage of damage than did Wrightsville Beach and Carolina Beach, where there were shore protection projects. The shore protection project at Wrightsville Beach is 14,000' in length, from Masonboro Inlet north to approximately Moores Inlet Street on Wrightsville Island. It does not provide protection to mainland Wrightsville Beach, Harbor Island (also part of Wrightsville Beach) or the northern part of the island of Wrightsville Beach (Shell Island). It is more appropriate to compare percent damages, which normalizes the damages, as opposed to absolute damage numbers because of the difference in demographics (median house value, number of housing units, land area, etc.) of the communities examined. Looking at damages (for those submitting FIA claims) as a percent of value, Wrightsville Beach and Caroline Beach had the lowest percentage of the property value damaged (**Figure 5-1** and **Table 5-4)**. Table 5-4 also displays the damage submitted for claims as a percentage of the communities' taxable property. This figure accounts for not only the number of structures but also for their value. Actual claims information is in **Table 5-5**. Note that the average claim paid reflects the cost of the structure. The average cost of a structure in Wrightsville Beach is most expensive, often more than double the costs of structures located in neighboring communities. It is also important to note that North Topsail Beach encompasses Coastal Barrier Resource Act (COBRA) areas, which cannot participate in the National Flood Insurance Program (NFIP), and therefore flood insurance is not available. Lack of claims in COBRA areas is *not* an indication of lack of damages.

> The NFI Program has paid more than $126.9 million in claims to 6,610 North Carolinians who suffered flood losses, an average of $19,193 per claim. Before Fran, 362 local governments were participating in the NFI Program in North Carolina. Since Fran, 29 more communities have joined and another 50 are taking the initial steps. There are 69,053 flood insurance policies in effect in the state, representing $7.8 billion in coverage. "After One Year, FRAN assistance tops $800 million. [FEMA *On-line News*] This is an increase from 61,198 polices with $6.5 billion in coverage in 1995. [NCHI *Insurance News Network*]

b. Structures Destroyed. Perhaps one of the most telling statistics is the number of structures destroyed. This is because the structures were largely destroyed by erosion and wave runup. This is the type of damage a shoreline protection project is designed to prevent, but the presence of a shoreline protection project does not guarantee the absence of damages in a community. Often flooding comes from back bay sources that cannot be prevented by an oceanfront shoreline protection project. Because the examined communities are barrier islands, they all experienced flooding from the sounds and rivers [Intracoastal Waterway] located between the islands and the mainland. Wrightsville Beach had no structures destroyed. Carolina Beach had only twenty structures destroyed (only two of which were oceanfront) and it is the community with the largest number of housing units. Both of these communities had a Corps shoreline protection project protecting them. The number of structures destroyed is shown in the last row of Table 5-4.

Figure 5-1
Property Values Versus Damages - Hurricane Fran

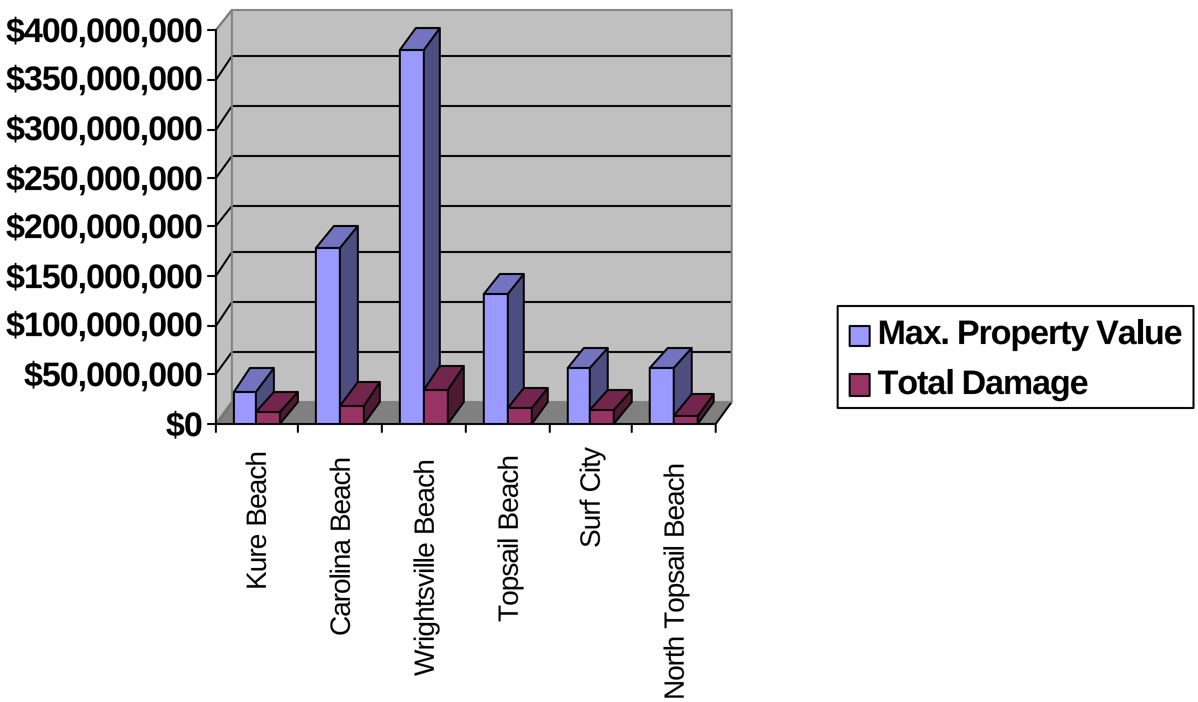

Table 5-4: Damages - Hurricane Fran

Item	Kure Beach	Carolina Beach	Wrightsville Beach 1/	Topsail Beach	Surf City	North Topsail Beach
Total Damage 2/	$11,079,701	$17,963,826	$35,124,130	$11,079,701	$15,121,149	$7,180,241
Maximum Property Value 2/	$33,083,619	$178,243,466	$379,053,231	$130,713,621	$57,733,091	$54,718,225
% Damage: Value	33%	10%	9%	12%	23%	13%
June 1996 Total Property Value 3/	$156,650,598	$440,061,463	$786,013,213	$194,365,237	$263,977,360	$274,177,870
Damage: Value	7%	45	4%	8%	5%	26% 4/
# of Structures Destroyed 5/	20	20 6/	0	30 7/	70 7/	320 7/

Source: Federal Insurance Administration claims database for Hurricane Fran event
Footnotes for Table 5-4 are provided on the following page.

Footnotes for Table 5-4:

1/ Corps project is 14,000' in length, from Masonboro Inlet north to approximately Moores Inlet Street. Approximately 500 of the approximately 1,200 claims paid were on mainland Wrightsville Beach, Harbor Island or north of the Corps project on Wrightsville Island, therefore not impacted at all by the project.
2/ For properties submitting FIA claims
3/ Each communities' Taxable Property Value = Tax Base x Assessment to Sales Ratio (from N.C. Department of Treasurer)
4/ Because many structures are in COBRA areas in North Topsail Beach and are not eligible to be in the NFIP, damages are severely understated. Damages used to compare to the total taxable properties are based on $72,000,000 in damages from an interview with local officials.
5/ Interviews with local officials.
6/ Of these 20 structures, only 2 were on the oceanfront.
7/ Many of these structures are not oceanfront and could have been destroyed even if a shore protection project had been in place.

Table 5-5: Claims Paid - Hurricane Fran

Item	Kure Beach	Carolina Beach	Wrightsville Beach 1/	Topsail Beach	Surf City	North Topsail Beach
# of FIA Claims	157	758	1,415	781	710	363 2/
# of Claims paid	128	676	1,203	664	522	273
Total Claims Paid	$10,069,998	$14,947,127	$30,280,128	$12,860,138	$11,184,761	$6,250,575
Average Claim Paid	$78,672	$22,111	$25,171	$19,368	$21,427	$134,348
# of Housing Units (1990)	1,126	3,342	2,413	1,005	2,339	2,173
# of Businesses	80	175	175	30	140	15

Footnotes:
1/ For the entire town of Wrightsville Beach and not just for the 14,000 foot long Corps oceanfront project.
2/ Many structures in North Topsail Beach are not eligible to be in the NFIP because they are in COBRA areas.

c. Oceanfront Property. **Table 5-6** examines claims of oceanfront properties only, which is part of the aggregated data in Table 5-4. These oceanfront properties are most likely to be impacted by a shoreline protection project. Once again, Wrightsville Beach and Carolina Beach have the lowest percentage of damage for submitted claims per property value. As expected, the differences in percent of property damaged is even greater for oceanfront properties than properties in the communities as a whole, reinforcing the concept that shoreline protection projects provide damage prevention and protection from surge and wave runup.

Table 5-6: Oceanfront Damages and Claims - Hurricane Fran

Item	Kure Beach	Carolina Beach	Wrightsville Beach 1/	Topsail Beach	Surf City	North Topsail Beach 2/
Oceanfront Damage 3/	$1,047,710	$2,432,973	$320,586	$5,572,490	$7,974,939	$3,564,484
Maximum Property Value 3/	$3,163,440	$21,967,852	$2,967,852	$29,166,794	$30,327,978	$19,168,391
% Damage: Value	33%	11%	13%	19%	26%	19%
# of Claims	12	85	13	200	231	131

Source: Federal Insurance Administration claims database for Hurricane Fran event

Footnotes:
1/ Corps project is 14,000' in length, from Masonboro Inlet north to approximately Moores Inlet Street.
2/ Many structures in North Topsail Beach are not eligible to be in the NFIP because they are in COBRA areas.
3/ For properties submitting claims.

5. Summary. Despite no significant differences in physical settings, Kure Beach (photos 5-1 through 5-4) and Topsail Island (photos 5-10 through 5-19) unprotected areas, sustained a greater percentage of damage than did Carolina Beach photos (5-5 and 5-6) and Wrightsville Beach (photos 5-7 through 5-9), where there were shore protection projects. In addition, there were no structures destroyed in Wrightsville Beach, while hundreds were destroyed in the communities on Topsail Island.

D. COMPLEXITIES WITH THE DATA

1. Localities. Each locality is unique with respect to protection from storms, value and age of structures, amount of oceanfront versus soundside development, etc. An examination of different communities illustrates the complexities associated with the attempt to collect and compare data.

a. Wrightsville Beach. To examine all the FIA data in Wrightsville Beach and credit it to a "protected shoreline" is not accurate. First, the north end of Wrightsville Island (Shell Island) is not protected by a Corps shoreline protection project. This area is characterized by newer housing (less than 30 years old) with large single family homes and multi-family high rise complexes. Harbor Island and mainland Wrightsville Beach are also not directly impacted by the Corps shoreline protection project. Of the 1,203 paid claims for the town of Wrightsville Beach, about 500 were attributed to Harbor Island and north of the Corps project on Wrightsville Island and some 360 claims were for structures located on the soundside of Wrightsville Island. No claims were paid for structures on mainland Wrightsville Beach. Only the approximately 330 remaining paid claims were in locations with protection provided by the Corps 14,000-foot project. The average for the 330 paid claims was $23,324, over $10,000 less than claims paid on the soundside or north of the project and $4,423 less than claims for Harbor Island. Although the average of $23,324 is higher than Carolina Beach, Topsail Beach and Surf City, the median house value in Wrightsville Beach is considerably higher than in the other communities, so one must look at the percent of damage to the properties' value.

b. Surf City. Surf City, located in the middle of Topsail Island, has varied levels of vulnerability. According to the Flood Insurance Rate Maps (FIRMs), the most vulnerable area is the ocean block of the Onslow County portion of Surf City, and this area indeed had a much greater percentage of its property damaged than any other part of Surf City. Though this area accounts for only 2/3 of a mile of oceanfront (of Surf City's 6.2 miles of oceanfront), roughly ten percent of the oceanfront, it accounts for about half of the structures destroyed in the town. Although the houses in this area are of lower average value than the remainder of the town, they incurred greater average damages per structure.

c. North Topsail Beach. Assessment of damages in North Topsail Beach is particularly problematic. FIA data presents an incomplete picture because the town contains COBRA areas where flood insurance is not available. Much of the data shown in the previous table had to be supplemented by interviews with local officials.

2. Rebuilding Options. Definitions of what structures were "greater than 50% damaged" and hence could not be rebuilt have been challenged by local homeowners. Land damage is even more problematic than damage to structures as demonstrated in the following example. A lawsuit was filed against the state of North Carolina by a construction company which alleged "illegal property seizure" in the aftermath of Hurricane Fran. The construction company had permission to build a 2,400-square-foot house in North Topsail Beach but had not begun construction when the storm wiped away the vegetation line, the defining mark for coastal building permits. After Hurricane Fran, the required minimum setback was unobtainable which barred construction of a habitable structure on the property. That, the company argues, violates state law prohibiting the taking of private property for a public purpose without just compensation. The rule has "denied Action Construction [company] all economically viable use of the property, and has destroyed the property's value", the suit says. The property, approximately half an acre according to Onslow County's Tax Office and three-quarters of an acre according to the suit, was last assessed in 1992 and is valued at $27,500, but the lot could easily sell for upwards of $100,000. Action Construction is seeking compensation "in excess of $10,000," the standard sought in such cases. [FEMA *On-line News*]

3. Flood Insurance Rate Map.

a. General. A Flood Insurance Rate Map (FIRM) is the official map of a community on which FEMA has delineated both the special flood hazard areas and the flood risk premium zones applicable to the community. The flood risk zones describe the risk of flooding. Zone V encompasses coastal areas subject to inundation by a 100-year flood having additional hazards associated with storm-induced waves. Zone A encompasses areas subject to inundation by a 100-year (1%-annual-chance) flood, while Zone B encompasses areas between the 100 and 500 year floods. Areas outside the 500-year floodplain are zone C. (Zone X is used on new and revised maps in lieu of zones B and C.)

b. FIRMs in the Study Area. Analysis of the damage by flood zone highlights the inadequacies of the FIRMs available in 1996. This situation is already recognized by FEMA and local government officials as stated in the Hurricane Fran *Building Performance Assessment* report. According to the FIRMs of the study area, many oceanfront lots are within B zones and C zones, outside the 100-year flood hazard. "Throughout the damaged oceanfront area, the effective FIRMs for the affected communities do not account for the effects of dune erosion, wave setup, or wave runup" [FEMA, BPA]. Because of this, simply looking at damage by FIRM zones is an inadequate comparison tool. Shoreline protection (or the lack there of) would have an impact on oceanfront homes, as well as some homes even beyond the oceanfront, many of which are listed in B or C zones.

4. Needs of Data Collection.

a. FIA Data. As previously stated, FIA claims are invaluable when evaluating damage and damage prevented due to the absence or presence of a shoreline protection project because flood insurance covers damage caused by storm surge, wave wash, tidal waves or overflow of any body of water from above-normal cyclical levels. Unfortunately, much of the FIA data is incomplete, often having no entry or an entry of "9999" for data fields that would allow an even more comprehensive analysis. If erosion and wave run-up were thoroughly evaluated in reporting of the claims, the differences would most likely show much greater differences. This lack of data entry is found in such fields as lowest floor elevation; base flood elevation; difference between lowest floor and zero damage elevations; building water depth; foundation type; wall construction and surface; flood characteristics; and hours water was in building. These are valuable additional pieces of information and partnering with FEMA and the FIA would pay dividends. See following paragraph 4c for additional information on this subject.

b. FEMA Efforts. Under similar efforts, FEMA contracted with the engineering firm Dewberry and Davis (D&D) to perform Global Positioning System (GPS) surveys of flooded buildings including post-disaster surveys following Hurricane Fran on Topsail Island. D&D found many problems with the geocoded tax parcels for the island which complicated their work (as well as the work of this study). The lack of information prior to actual storm events was the largest deficiency to accurate storm damage assessment in D&D's opinion. D&D recommended that "six attributes should be collected for all buildings in or near floodplains: geocoded addresses; geocoded parcels; names of owners; three-dimensional surveys of floodprone buildings; total parcel and footprint areas; and replacement values." With this information D&D stated, "when floods actually occur, it is no longer necessary to survey individual buildings to determine their depth of flooding. Instead, one can determine the high water marks at several key locations in town and model the flood water elevations. By knowing the peak flood elevations and lowest floor elevations, the depth of interior flooding can be quickly determined. Combined with data on floor area and pre-flood replacement value, actual flood damages can be quickly and accurately estimated for every flooded building in the community" http://www.dewberry.com/fip/ProfessionalForum/maunepaper.htm.

c. Corps Post Storm Survey Data. In the majority of cases, Corps coastal projects do not receive post storm surveys. This fact was noted and found to be a deficiency in two recent national studies: "*Beach Nourishment and Protection*" by the Marine Board of the National Research Council [National Academy Press, Washington, D.C. 1995] and "*Shoreline Protection and Beach Erosion Control Study, Final Report: An Analysis of the U.S. Army Corps of Engineers Shore Protection Program*," IWR Report 96-PS-1. The North Carolina Disaster Recovery Task Force convened after Hurricane Fran had associated recommendations such as to develop consistent damage assessment methodologies, housing data and an economic data collection system. For the study areas of North Carolina, the Corps' Wilmington District advised that they did not perform comprehensive post storm surveys due to lack of funding. Examples of valuable data that should be collected are shown in **Appendix F**.

E. REFERENCES

The Federal Emergency Management Agency Region IV, *On-line News*, Atlanta, August 25, 1997. "After One Year, FRAN Assistance Tops $800 million."

"North Carolina Home Insurance," *Insurance News Network*, website http://www.insure.come/states/nc/home/index.html.

The Federal Emergency Management Agency Mitigation Directorate, FEMA 290/March 19, 1997. "Building Performance Assessment: Hurricane Fran in North Carolina," p2-38.

CHAPTER 6
FINDINGS AND CONCLUSIONS

A. FINDINGS

1. Winds.
   - Based on the best available wind speed data, the overall onshore wind speed patterns were not significantly different for the four beach areas, although slightly higher winds did exist at the southern beaches of Kure – Carolina – Wrightsville, than at the northern end of the study area (Topsail Island).
   - Differences in winds can not explain the differences in damage experienced at the protected areas of Carolina Beach and Wrightsville Beach and the unprotected areas of Kure Beach and the three communities on Topsail Island.

2. Storm Surge.
   - While modeled surge elevations did not vary greatly over the study area (maximum differential of 1.2 feet), elevations were highest at the protected Wrightsville Beach and lowest at the unprotected communities on Topsail Island.
   - The non-variability of the storm surge results from the path of the storm and the similarity of offshore bathymetric contours.
   - Differences in storm surge can not explain the differences in damage experienced at the protected areas of Carolina Beach and Wrightsville Beach and the unprotected areas of Kure Beach and the three communities on Topsail Island.
   - Hurricane Fran occurred at low tide. Had it occurred at high tide, as did Bertha, damages would have been greater.

3. Waves.
   - Waves were modeled in four parameters: significant wave height, peak wave period, offshore wave height, and combined wave/surge heights. While these four sets of data did not vary greatly over the study area; the highest modeled data were at the protected Wrightsville Beach area, followed by the Kure and Carolina Beaches that had identical data, and with the lowest values occurring at the unprotected Topsail Island beaches.
   - The wave climate offshore was about 1 to 2 meters greater at the Kure – Carolina-Wrightsville Beach area than it was at Topsail Island.
   - The model data showed that the Wrightsville Beach area was the most severely impacted because of the combined offshore wave climate, the steep offshore wave height gradients and landward migration of the wave estimates caused by surge.
   - Differences in waves can not explain the differences in damage experienced at the protected areas of Carolina Beach and Wrightsville Beach and the unprotected areas of Kure Beach and the three communities on Topsail Island.

4. High Water Marks.
   - Excluding Kure Beach, the trend of the high water mark was not significantly different over the study area and followed the trend of the computed storm surge elevations, with the highest being at the protected Wrightsville Beach and the lowest being at the unprotected Topsail Island beaches.
   - The highest still water marks were measured along the south end of Kure Beach. These high water marks were believed to be due to a combination of high landmass that produced some wave standing and localized wave phenomena due to submerged Coquina Rock outcrops.
   - The surge and wave modeling efforts were not detailed enough to capture the localized impacts of the Coquina Rock Outcrop or the higher land elevations along Kure Beach.
   - Except for the damage experienced at the southern end of Kure Beach, differences in high water marks can not explain the differences in damage experienced at the protected areas of Carolina Beach and Wrightsville Beach and the unprotected areas of Kure Beach and the three communities on Topsail Island.

5. Geology.
   - Offshore geology varies from Kure Beach to North Topsail Beach and contributed to differences in prestorm beach conditions. The areas with existing wide beaches and dune systems, either man-made or natural, experienced less storm damage.
   - Impacts from the physical storm parameters of waves and surge were not influenced by the offshore geology except for the Kure beach area which has a Coquina Rock formation in the near shore region.
   - The prestorm condition of the beach helps to explain the lesser damages at the protected areas and greater damages at the unprotected areas.

6. Economic Damage Assessment.
   - In terms of demographics, Wrightsville Beach and Carolina Beach are more densely populated and have higher housing values than do Kure Beach and the three beach communities on Topsail Island.
   - The three communities on Topsail Island and Kure Beach, all unprotected areas, sustained a greater percent of damages than did the protected areas of Wrightsville Beach and Carolina Beach.
   - No structures were destroyed at the protected Wrightsville Beach while hundreds were destroyed in the unprotected areas on Topsail Island.
   - On Topsail Island, data on destroyed properties were not available to separate "oceanfront properties" from the total.
   - Kure Beach and Carolina Beach experience essentially the same storm factors. While Carolina Beach experienced higher damage in absolute dollars (due to a larger

number of structures and a higher housing value within the town limits), Kure Beach experienced a higher percentage of ocean front structural damage.

- Claim and damage value was difficult to obtain and much of the FIA data were incomplete. Corps partnering with FEMA and FIA in collecting after storm data would pay dividends.
- If erosion and wave run-up were thoroughly evaluated in reporting claims, the differences between protected and unprotected areas would most likely be greater.
- Lack of information prior to actual storm events was the largest deficiency to accurate storm damage assessment.

7. Photos Comparing Damages

Photo 6-1: Wrightsville Beach after Hurricane Fran

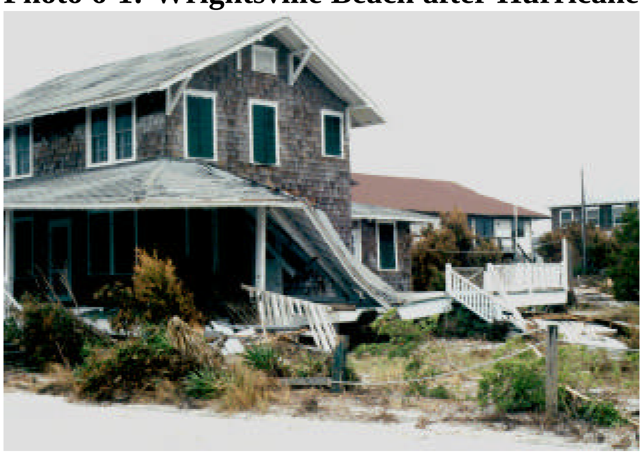

Photo 6-2: North Topsail Beach after Hurricane Fran

Photo 6-3: Carolina Beach after Hurricane Fran

Photo 6-4: Kure Beach after Hurricane Fran

B. CONCLUSIONS

- The areas protected by Corps of Engineers shore protection projects (Wrightsville Beach and Carolina Beach) received less damage as a percent of total property value than did the unprotected areas (Kure Beach, Topsail Beach, Surf City and North Topsail Beach).
- While differences in physical storm parameters (winds, storm surge and waves) were observed from Kure Beach to North Topsail Beach, the differences were not large enough to explain the differences in damage. If anything, storm parameters showed the most devastating part of the storm hit Wrightsville Beach and the less devastating part of the storm hit Topsail Island.
- Offshore geology, which varies from Kure Beach to Topsail Island, likely contributed damages and the lack of damages.
    - At the south end of Kure Beach is a Coquina rock outcrop that contributed to the highest of the highwater to be observed at this location and resulted in an increase in damages.
    - The areas with existing wide beaches and a frontal dune system, either natural or man-made, experienced less storm damage..
- Partnering with agencies such as the Federal Emergency Management Agency and the Federal Insurance Administration in collecting damages data through post storm surveys and distinguishing between flooding and erosion damages would pay dividends.

C. SUMMARY

Beach nourishment projects similar to the ones at Carolina Beach, Wrightsville Beach and now at Kure Beach do reduce hurricane storm damages, which, in turn, reduce Federal disaster recovery costs.

APPENDIX A
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(1) Transferred to the Buffalo District (CELRD-PM-PL), September 2000.

APPENDIX B
GENERIC SHORE PROTECTION LEGISLATION

1. PL 71-520, (1930) River and Harbor Act of 1930. Section 2 authorizes the Chief of Engineers to conduct shore erosion control studies in cooperation with appropriate agencies of various cities, counties, or states. Amended by Section 103, PL 86-465. Section 2 also established the Beach Erosion Board to act as a central agency to assemble data and provide engineering expertise regarding coastal protection.

2. PL 79-166, (1945) An Act Authorizing General Shoreline Investigations at Federal Expense. This Act established authority for the Beach Erosion Board to pursue a program of general investigation and research and to publish technical papers.

3. PL 79-526, (1946) River and Harbor Act of 1946. Section 14 authorized emergency bank protection works to prevent flood damage to highways, bridge approaches and public works. Amended by PL 93-251, PL 99-662 and PL 104-303.

4. PL 79-727, (1946) An Act Authorizing Federal Participation in the Cost of Protecting the Shores of Publicly Owned Property. This Act authorized Federal participation in the study cost, but not the construction or maintenance, of works to protect publicly-owned shores of the United States against erosion from waves and currents. Amended by PL 84-826, PL 87-874, PL 91-611 and PL 104-303.

5. PL 84-71, (1955). This legislation specifically authorized studies of the coastal and tidal areas of the eastern and southern U.S. with reference to areas where damages had occurred from hurricanes.

6. PL 84-99, (1955). This legislation authorized the Chief of Engineers to provide emergency protection to threatened Federally authorized and constructed hurricane and shore protection works. It also established an emergency fund to repair or restore such works damaged or destroyed by wind, wave, or water action of other than an ordinary nature.

7. PL 84-826, (1956). This legislation expanded the Federal role by authorizing Federal participation in the cost of works for protection and restoration of the shores of the United States, including private property if such protection is incidental to the protection of public-owned shores, or if such protection would result in public benefits. It also provides for Federal assistance for period nourishment on the same basis as new construction, for a period to be specified by the Chief of Engineers, when it would be the most suitable and economical remedial measure. Amended by Section 156, PL 94-587 and Section 934, PL 99-662.

8. PL 85-500, (1958) River and Harbor Act of 1958. Section 203 added provisions of local cooperation on three hurricane flood protection projects which established an administrative precedent for cost sharing

in hurricane projects. Non-Federal interests were required to assume 30 percent of total first costs, including the value of land, easements and rights of way, and operate and maintain the projects.

9. PL 87-874, (1962) River and Harbor Act of 1962.

a. Shore Protection. Section 103 amended Section 3 of the Act approved 13 August 1946, as amended by the Act approved 28 July 1956 and indicated the extent of Federal participation in the cost of beach erosion and shore protection (50 percent of the construction cost when the beach is publicly owned or used, and 70 percent Federal participation for seashore parks and conservation areas when certain conditions of ownership and use of the beaches are met). Amended by Section 112, PL 91-611 and Section 915(e), PL 99-662.

b. Small Beach Erosion Projects. Section 103 also authorized the Secretary of the Army acting through the Chief of Engineers, to plan and construct small beach and shore protection projects without specific Congressional authorization. Federal cost share was limited to $400,000 per project and $3 million program limit per fiscal year.

10. PL 88-172, (1963). Section 1 of this legislation abolished the Beach Erosion Board, transferred its review functions to the Board of Engineers for Rivers and Harbors and established the Coastal Engineering Research Center.

11. PL 89-72, (1965) The Federal Water Project Recreation Act of 1965. This Act required that planning of water resources projects consider opportunities for outdoor recreation and fish and wildlife enhancement. It specified that the outdoor recreation benefits that can be attributed to a project shall be taken into account in determining the overall benefits of the project (e.g., recreational use of beach fill, groins or other shore protection structures).

12. PL 89-298, (1965). This legislative action allowed Federal contributions toward periodic nourishment.

13. PL 90-483, (1968) River and Harbor and Flood Control Act of 1968.

a. Section 111. This section authorized investigation and construction of projects to prevent or mitigate shore damages resulting from Federal navigation works, at both public and privately-owned shores along the coastal and Great Lakes shorelines. Cost is to be at full Federal expense, but limited to $1 million per project. Amended 17 November 1986 by Sections 915(f) and 940, PL 99-662 which, among other things, increased the limit on Federal costs per project to $2 million for initial construction costs. There is no limit on in Federal participation in periodic nourishment costs.

b. Section 215. This section authorized reimbursement (including credit against local cooperation requirements) for work performed by non-Federal public bodies after authorization of water resource development projects. Execution of a prior agreement with the Corps was required and reimbursement was not to exceed $1 million for any single project. Amended by Section 913 PL 99-662 and by Section 12, PL 100-676 to increase the limit on reimbursements per project. Project limit is now $3 million or one percent of the total project cost, whichever is greater; except that the amount of actual Federal reimbursement, including reductions in contributions, for such project may not exceed $5 million in any fiscal year.

14. PL 91-611, (1970) River and Harbor and Flood Control Act of 1970.

a. Section 112. This section increased the limit on Federal costs for small beach erosion projects (Section 103 of PL 87-874) from $500,000 to $1 million. The annual authorization limit was also raised to $25,000,000. Limits have subsequently been raised further, most recently by PL 99-662 to $2 million per project and $30 million program limit per year.

b. Section 208. This section authorized discretionary modifications in Federal participation in cost sharing for hurricane protection projects.

15. PL 92-583, (1972) The Coastal Zone Management Act of 1972. This Act required all Federal agencies with activities directly affecting the coastal zone, or with development projects within that zone, to assure that those activities or projects are consistent with the approved state program. The CZMA of 1972 was amended by the Coastal Zone Management Act Amendments of 1990. The 1990 Act amended the Federal consistency provisions (Section 307) by requiring all Federal agency activities, whether in or outside of the coastal zone, to be subject to the consistency requirements of Section 307(c) of the CZMA if they affect natural resources, land uses or water uses in the coastal zone.

16. PL 93-251, (1974) Water Resources Development Act of 1974.

a. Section 27. This section raised the cost limits for emergency bank protection projects (Section 14 projects) to $250,000 and program fiscal funding limit to $10 million per year. Project purpose was extended to cover construction, repair, restoration and modification of emergency streambank and shoreline protection works. Eligibility definition was extended to include churches, hospitals, schools and similar non-profit public services. Amended by Section 915 (c) of PL 99-662 and Section 219 of PL 104-303.

b. Section 55. This section authorizes technical and engineering assistance to non-Federal public interests in developing structural and non-structural methods of preventing damages attributable to shore and streambank erosion.

17. PL 94-587, (1976) Water Resources Development Act of 1976.

a. Section 145. This section authorized the placement of beach quality sand obtained from dredging operations on adjacent beaches if requested by the interested state government and in the public interest--with the increased costs paid by local interests. Amended by Section 933, PL 99-662, to allow for Federal funding of 50 percent of the increased costs; by Section 207 of PL 102-580 to permit agreements for placement of fill on beaches to be with political subdivisions of a state; and by Section 217 of PL 106-53 by lowering the Federal share of the extra costs from 50 percent to 35 percent.

b. Section 156. This section authorizes the Corps to extend Federal aid in periodic beach nourishment up to 15 years from date of initiation of construction. Amended by Section 934 of PL 99-662 to allow for extension of up to 50 years.

18. PL 97-348, (1982) The Coastal Barrier Resources Act of 1982. This law established the policy that coastal barrier islands and their associated aquatic habitats are to be protected by restricting Federal expenditures which encourage development on those coastal barrier islands. The Act also provides for a Coastal Barrier Resources System (the extent of which is defined by a set of maps approved by Congress on 30 September 1982) which identifies undeveloped coastal barriers within which Federal expenditures (including expenditures for flood insurance, roads, bridges, shoreline structures) may not be made. Specific exceptions to the expenditure prohibition include navigation, beach nourishment, and research works. The Act was amended in 1990. To ensure compliance with the Act, each Federal agency annually certifies compliance directly to the Senate and House Committees on Public Works and Transportation.

19. PL 99-662, (1986) Water Resources Development Act of 1986.

a. Section 101(c). This section provides that costs of constructing projects or measures for the prevention or mitigation of erosion or shoaling damages attributable to Federal navigation works shall be shared in the same proportion as the cost sharing provisions applicable to the project causing such erosion or shoaling. The non-Federal interests for the project causing the erosion or shoaling shall agree to operate and maintain such measures.

b. Section 103. Section 103(d) specifies that the costs of constructing projects for beach erosion control must be assigned to selected project purposes such as hurricane and storm damage reduction, and/or recreation. Cost sharing for these project purposes is specified in Section 103(c) (35 percent for hurricane and storm damage prevention and 50 percent for separable recreation). However, all costs assigned to benefits to privately-owned shores (where use of such shores is limited to private interests), or to prevention of losses of private lands are a non-Federal responsibility. All cost assigned to protection of Federally-owned shores are a Federal responsibility. Amended by Section 215, PL 106-53, to increase non-Federal cost sharing for periodic nourishment.

c. Section 915. Section 915(c) increased the Federal limits up to $500,000 for participating in emergency shoreline protection of public works (Section 14 projects). Section 915(e) increased the Federal limits up to $2 million for participating in small beach erosion control (Section 103 projects). Section 915(f) increased the Federal limits up to $2 million for participating in mitigation of shore damage attributable to Federal navigation works (Section 111 projects). Section 915(h) authorizes use of Section 103 of PL 87-874 and Section 111 of Pl 90-483 authorities in the Trust Territory of the Pacific Islands.

d. Section 933. This section modifies Section 145 of PL 94-587 to authorize 50 percent Federal cost sharing of the extra costs for using dredged sand from Federal navigation improvements and maintenance efforts for beach nourishment.

e. Section 934. Section 934 modifies Section 156 of PL 94-587 to authorize the Secretary of the Army, acting through the Chief of Engineers to extend aid in periodic nourishment up to 50 years from the date of initiation of project construction.

f. Section 940. This section amends Section 111 of PL 90-483 to allow implementation of nonstructural measures to mitigate shore damages resulting from Federal navigation works; to require local interests to operate and maintain Section 111 measures; and to require cost sharing of implementation costs in the same proportion as for the works causing the shore damage.

20. PL 100-676, (1988) Water Resources Development Act of 1988. Section 14 of the Act requires non-Federal interests to agree to participate in and comply with applicable Federal flood plain management and flood insurance programs before construction of any hurricane and storm damage reduction project.

21. PL 102-580, (1992) Water Resources Development Act of 1992. Under Section 206, non-Federal interests are authorized to undertake shoreline protection projects on the coastline of the United States, subject to obtaining any permits required pursuant to Federal and State laws in advance of actual construction, and subject to prior approval of the Secretary of the Army.

22. PL 104-303, (1996) Water Resources Development Act of 1996.

a. Section 207. Directs that in carrying out navigation projects, the secretary may select a disposal method that is not the least cost option if the incremental costs are reasonable in relation to the environmental benefits including creation of wetlands and shoreline erosion control.

b. Section 219. This section increases the emergency bank protection projects (Section 14 projects) to $1 million per project and $15 million program limit per year.

c. Section 227. This section amends 33 U.S.C. 426e (Section 14 of PL 79-727, as amended) to clarify Federal shore protection policy to apply to shores and beaches. Encourages the protection, restoration and periodic nourishment, on a coordinated Federal/non-Federal basis, with a priority given to those areas where a Federal investment already occurs or where damage has been caused by a Federal action.

23. PL 106-53 (1999) Water Resources Development Act of 1999.

a. Section 215. This section modifies Section 103(d) of PL 99-662 by changing "Costs of construction" to "CONSTRUCTION. - Costs of construction" and by changing the non-Federal share of periodic nourishment costs to 45 percent after January 1, 2002 and to 50 percent after January 1, 2003. This is for projects in reports authorized for construction after these dates.

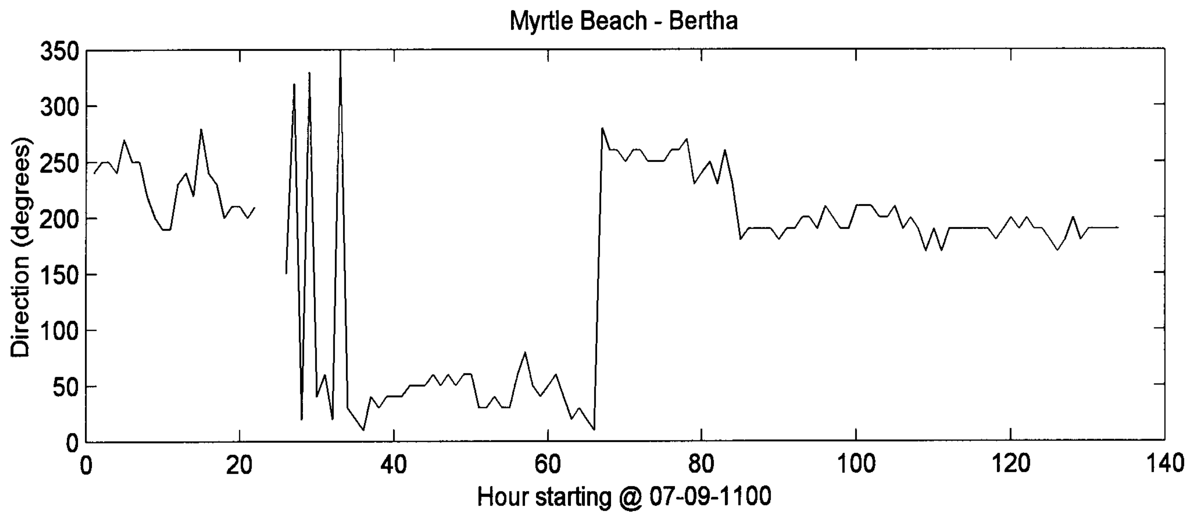
b. Section 217. This section further modifies Section 145 of PL 94-587 by lowering the Federal share of the extra costs for using dredged sand from Federal navigation improvement and maintenance efforts for beach nourishment from 50 percent to 35 percent.

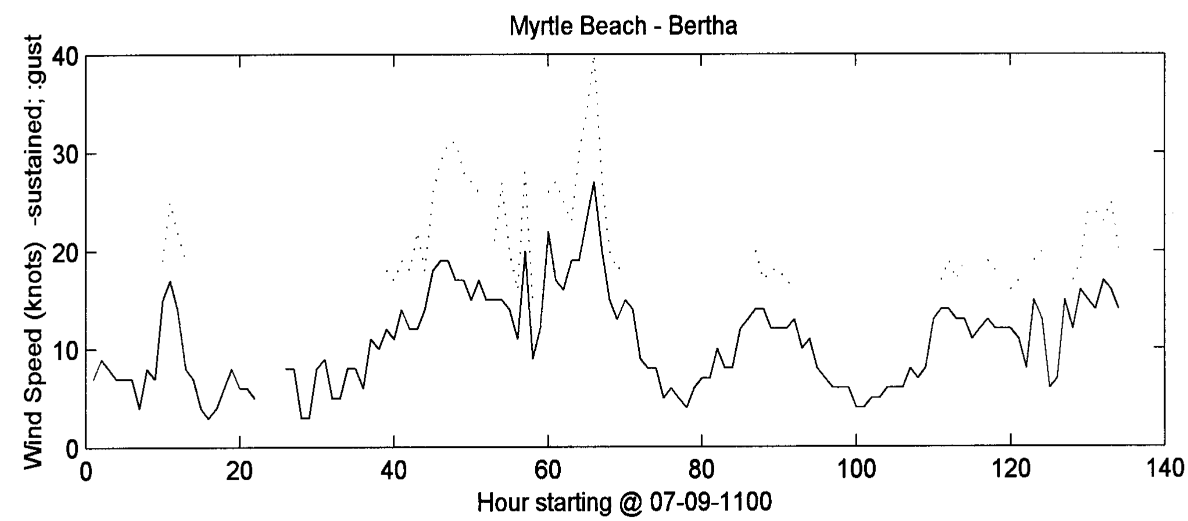
24 PL 106-541 (2000) Water Resources Development Act of 2000. Section 220 of this act requires that not later than one year after 11 December 2000, the Secretary shall develop and implement procedures to ensure that all of the benefits of a beach restoration project, including those benefits attributable to recreation, hurricane and storm damage reduction, and environmental protection and restoration, are displayed in reports for such projects.

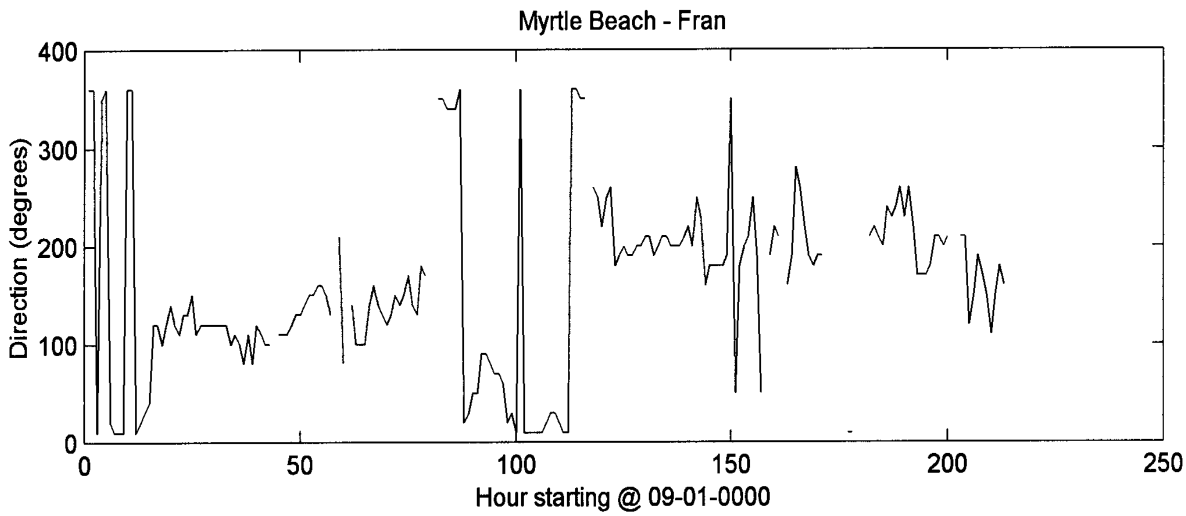
APPENDIX C
WINDS

TABLE OF CONTENTS

Plots of Wind Speed and Direction at Onshore Stations (Myrtle Beach, Wilmington, New River, and Cherry Point)






Myrtle Beach - Fran
Direction (degrees)
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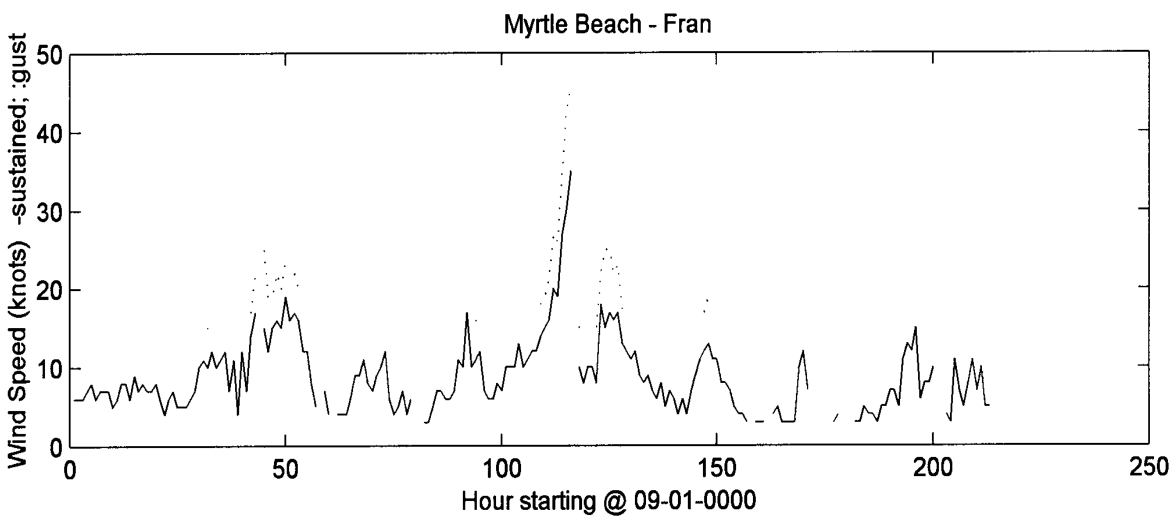
200
100
0
0
50
100
150
200
250
Hour starting @ 09-01-0000


Myrtle Beach - Fran
Wind Speed (knots) -sustained; :gust
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200
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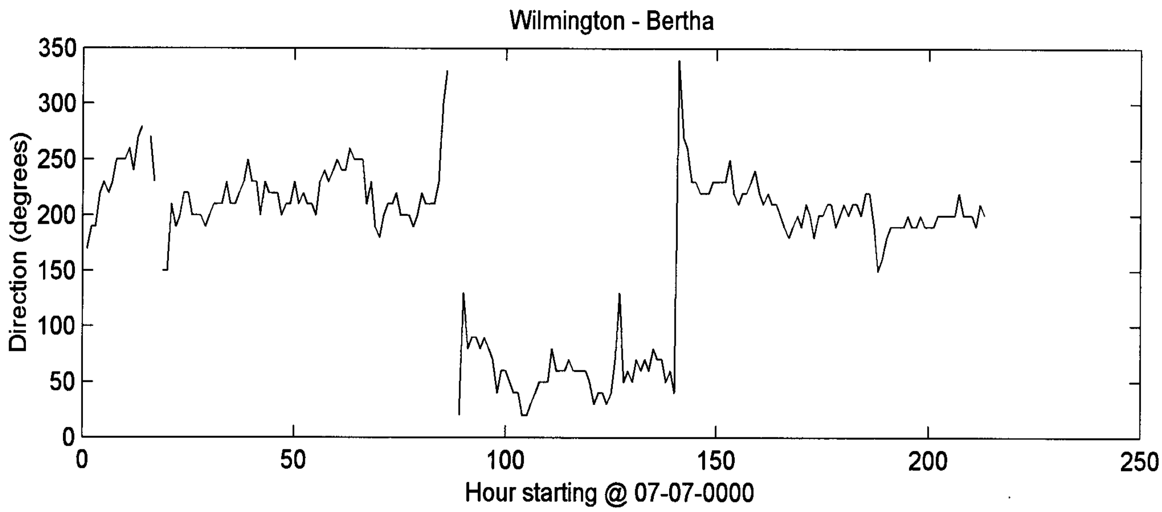
Hour starting @ 09-01-0000


Wilmington - Bertha
Direction (degrees)
Hour starting @ 07-07-0000
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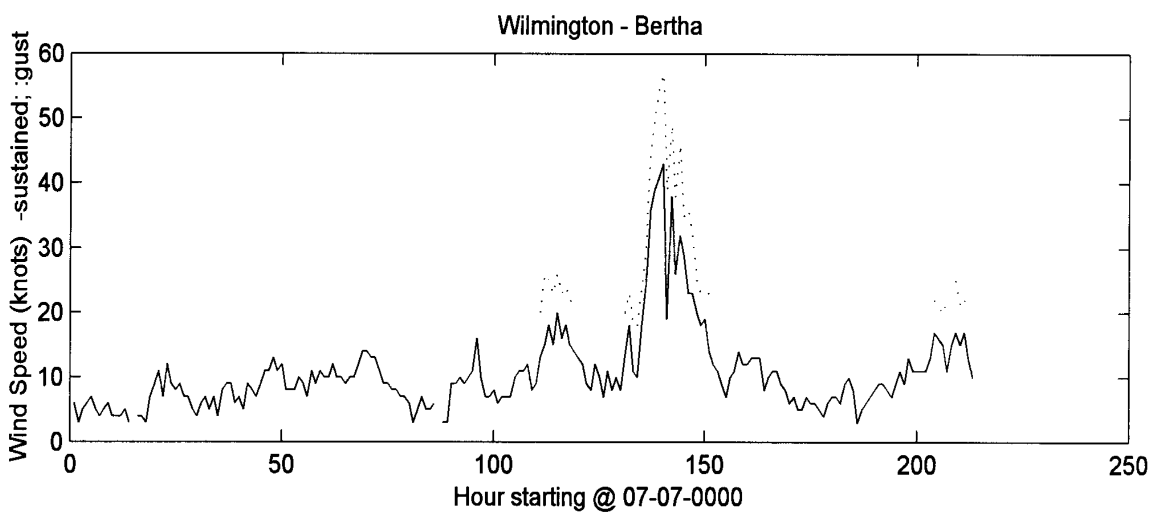
100
150
200
250
300
350


Wilmington - Bertha
Wind Speed (knots) -sustained; :gust
Hour starting @ 07-07-0000
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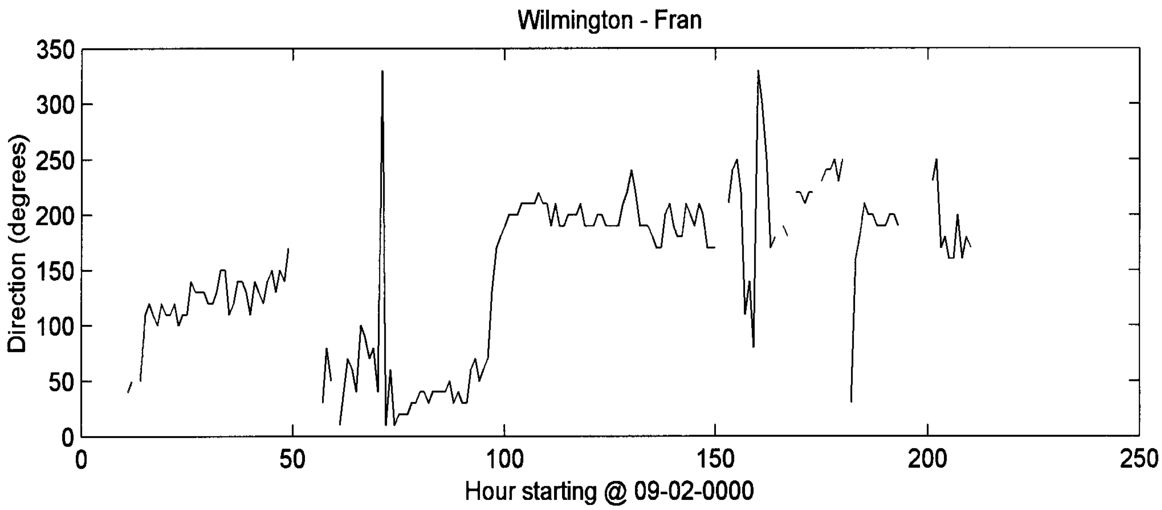
Wilmington - Fran
Direction (degrees)
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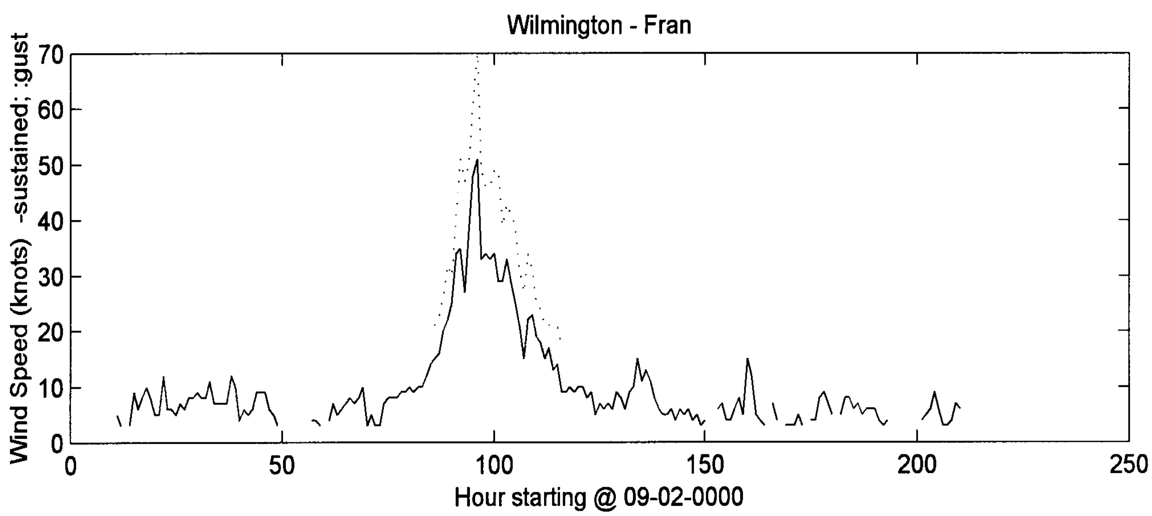
Hour starting @ 09-02-0000


Wilmington - Fran
Wind Speed (knots) -sustained; :gust
70
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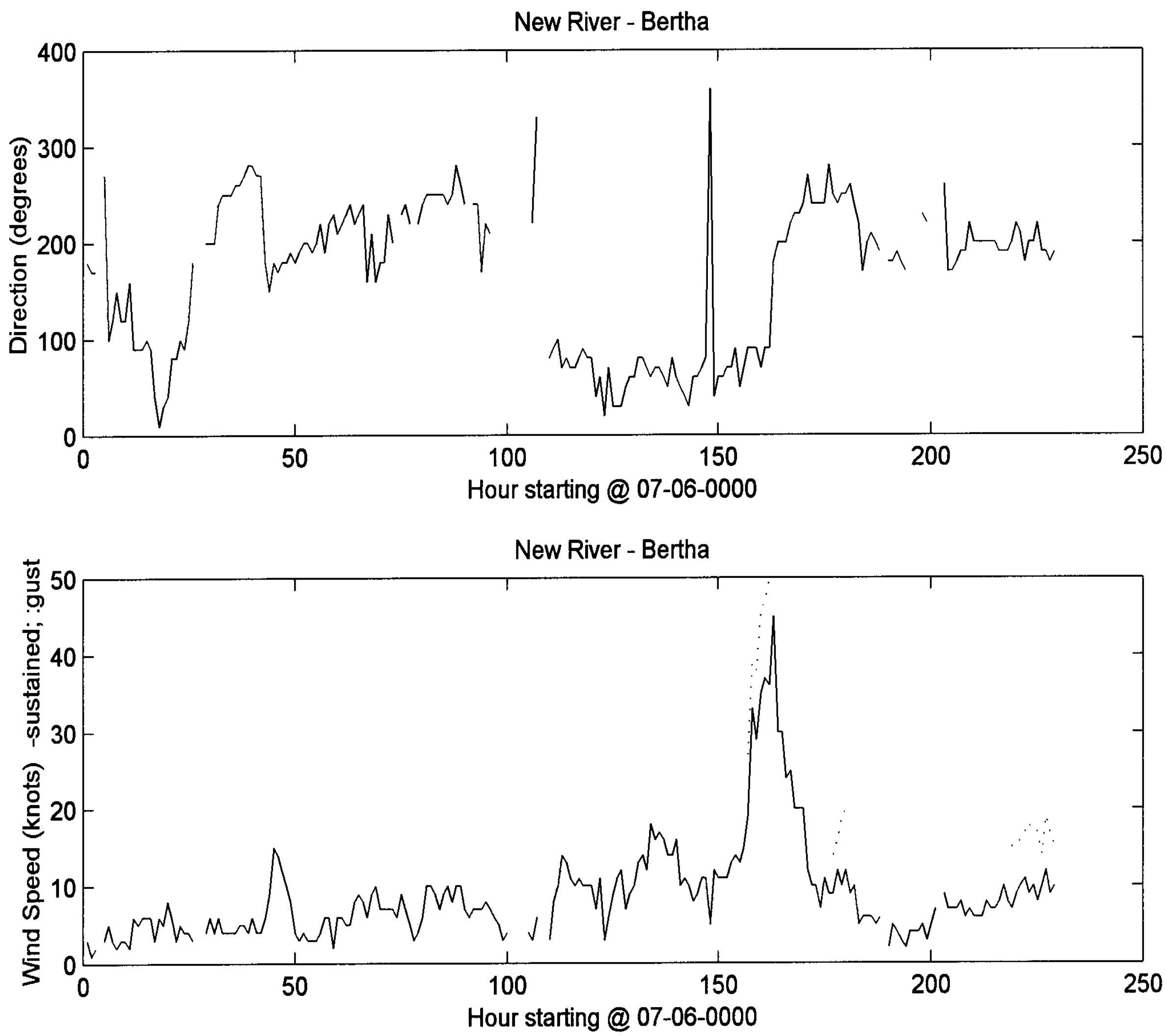
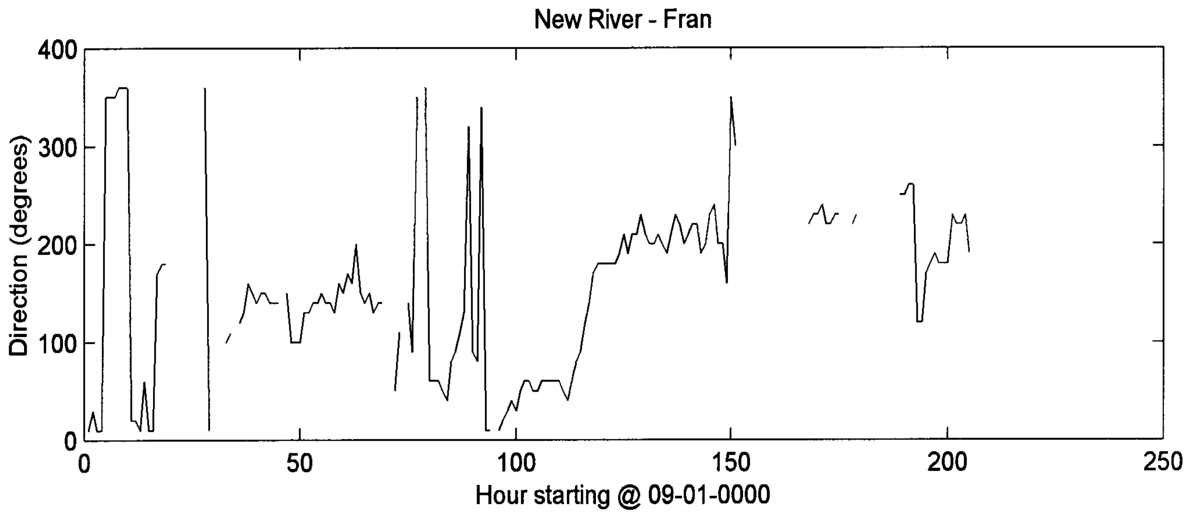
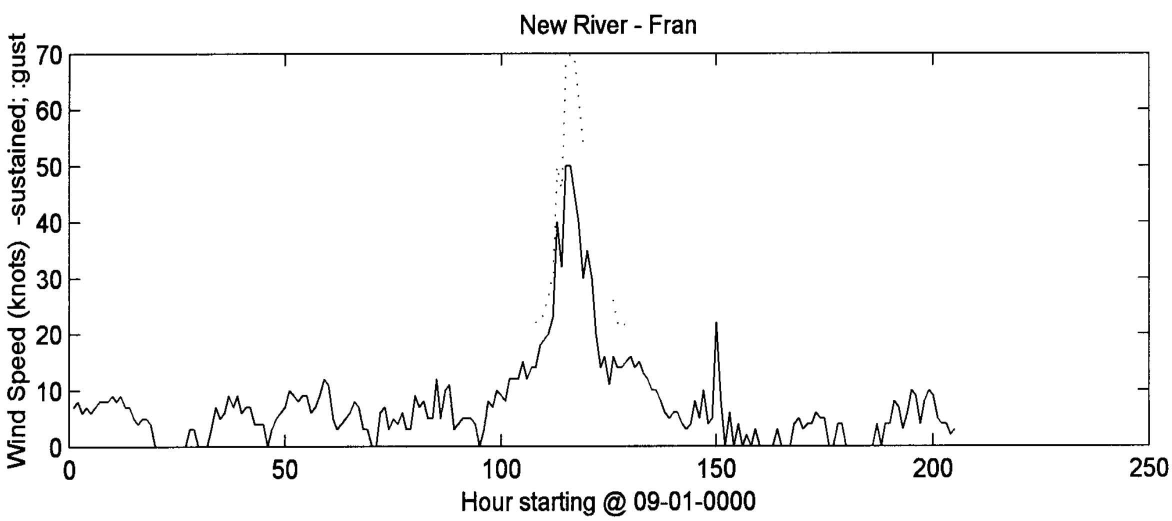
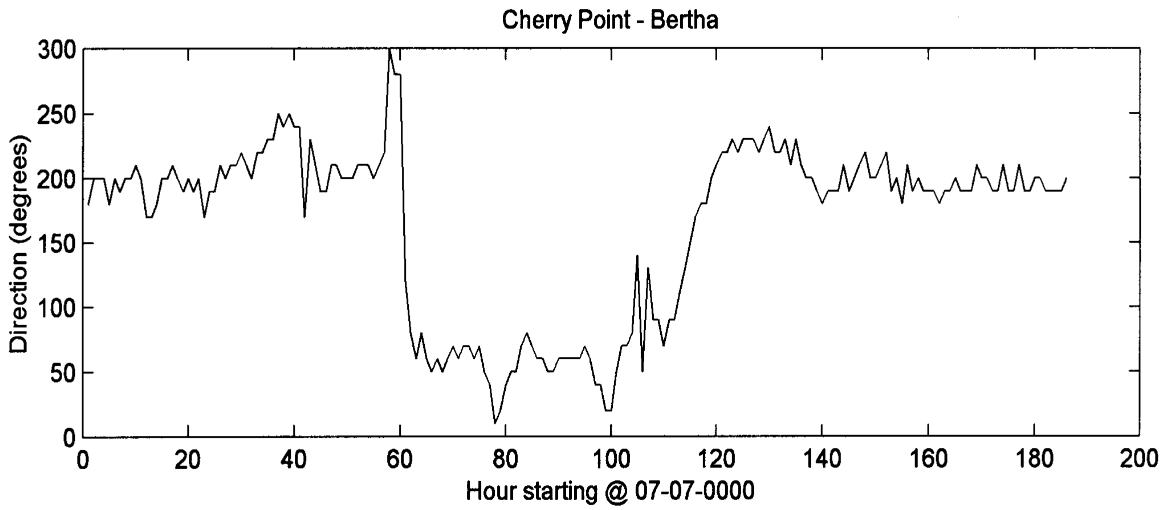
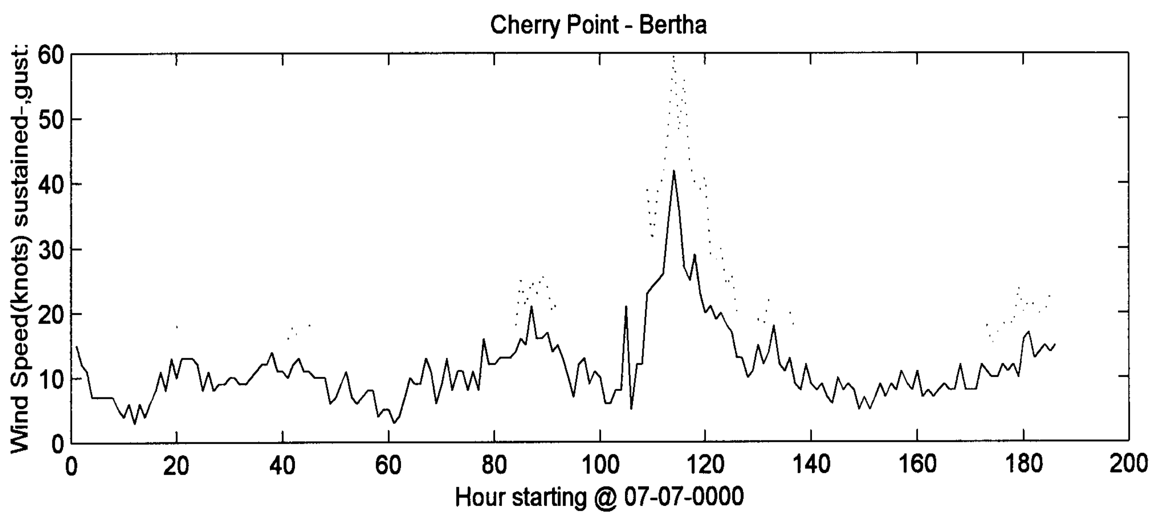
250
Hour starting @ 09-02-0000

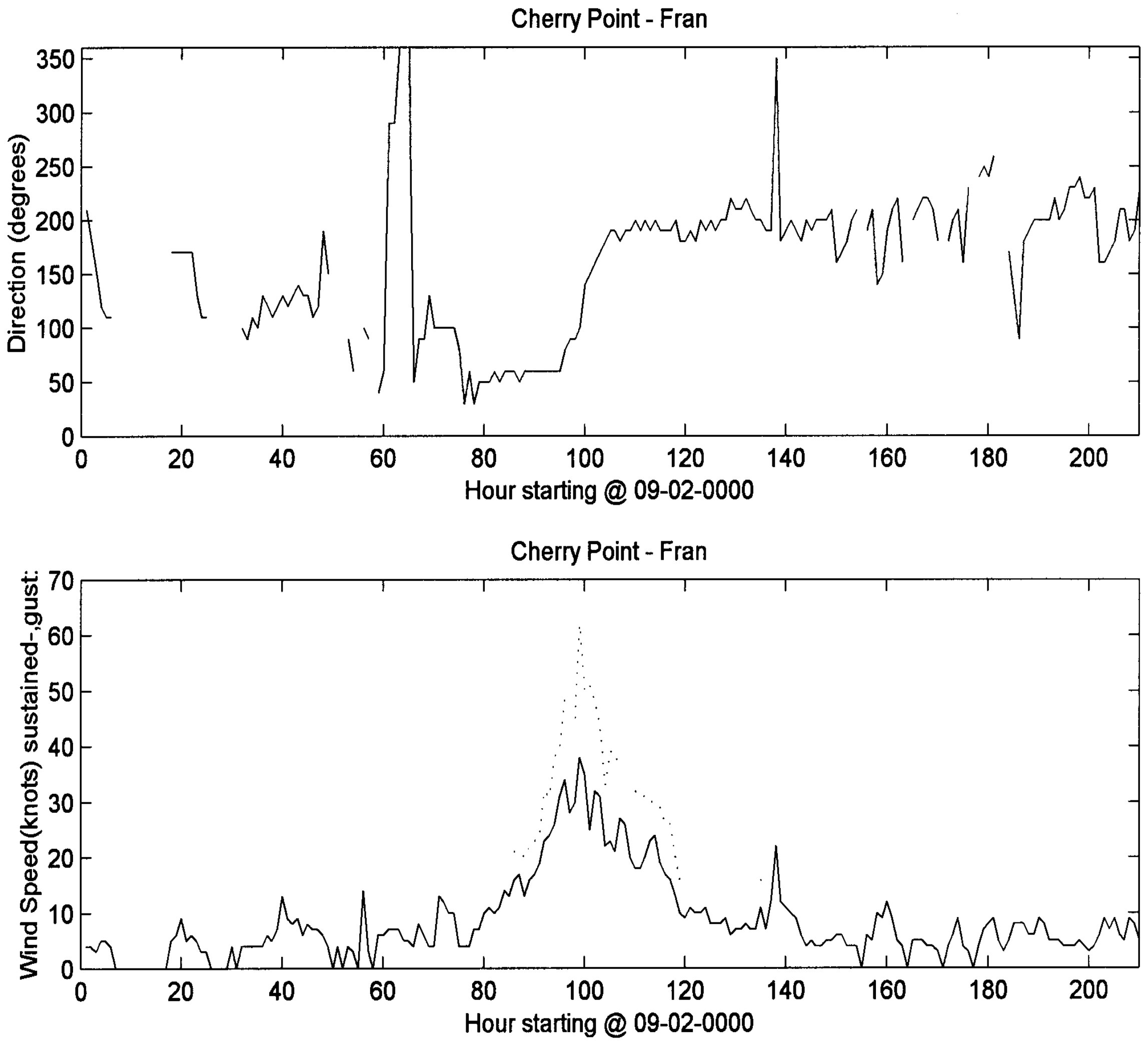

New River - Bertha
Direction (degrees)
400
300
200
100
0
0
50
100
150
200
250
Hour starting @ 07-06-0000
New River - Bertha
Wind Speed (knots) -sustained; :gust
50
40
30
20
10
0
0
50
100
150
200
250
Hour starting @ 07-06-0000


New River - Fran
Direction (degrees)
Hour starting @ 09-01-0000
0
100
200
300
400
50
150
250


New River - Fran
Wind Speed (knots) -sustained; :gust
Hour starting @ 09-01-0000
0
10
20
30
40
50
60
70
100
150
200
250


Cherry Point - Bertha
Direction (degrees)
Hour starting @ 07-07-0000
0
50
100
150
200
250
300
0
20
40
60
80
100
120
140
160
180
200


Cherry Point - Bertha
Wind Speed(knots) sustained-,gust:
Hour starting @ 07-07-0000
0
10
20
30
40
50
60
0
20
40
60
80
100
120
140
160
180
200


Cherry Point - Fran
Direction (degrees)
Hour starting @ 09-02-0000
Cherry Point - Fran
Wind Speed(knots) sustained-,gust:
Hour starting @ 09-02-0000

Reading of Wind Speed and Direction at Wilmington, NC
Hurricane Bertha

		Yr	Mo	Da	Hr	Dir	Sus	Gust
						(Knots		)
723013	KILM	1996	07	01	0900	240	008	NaN
723013	KILM	1996	07	01	1000	240	009	NaN
723013	KILM	1996	07	01	1034	260	007	NaN
723013	KILM	1996	07	01	1048	270	006	NaN
723013	KILM	1996	07	01	1100	260	006	NaN
723013	KILM	1996	07	01	1106	260	007	NaN
723013	KILM	1996	07	01	1200	260	005	NaN
723013	KILM	1996	07	01	1300	270	006	NaN
723013	KILM	1996	07	01	1400	290	005	NaN
723013	KILM	1996	07	01	1500	300	007	NaN
723013	KILM	1996	07	01	1600	350	006	NaN
723013	KILM	1996	07	01	1700	350	007	NaN
723013	KILM	1996	07	01	1800	330	008	NaN
723013	KILM	1996	07	01	1900	NaN	004	NaN
723013	KILM	1996	07	01	2000	340	006	NaN
723013	KILM	1996	07	01	2100	010	007	NaN
723013	KILM	1996	07	01	2200	020	006	NaN
723013	KILM	1996	07	01	2300	350	003	NaN
723013	KILM	1996	07	02	0000	NaN	000	NaN
723013	KILM	1996	07	02	0026	NaN	000	NaN
723013	KILM	1996	07	02	0045	NaN	000	NaN
723013	KILM	1996	07	02	0100	NaN	000	NaN
723013	KILM	1996	07	02	0200	NaN	000	NaN
723013	KILM	1996	07	02	0300	NaN	000	NaN
723013	KILM	1996	07	02	0336	NaN	000	NaN
723013	KILM	1996	07	02	0400	NaN	000	NaN
723013	KILM	1996	07	02	0411	NaN	000	NaN
723013	KILM	1996	07	02	0500	NaN	000	NaN
723013	KILM	1996	07	02	0600	NaN	000	NaN
723013	KILM	1996	07	02	0627	030	003	NaN
723013	KILM	1996	07	02	0639	050	003	NaN
723013	KILM	1996	07	02	0700	NaN	000	NaN
723013	KILM	1996	07	02	0706	NaN	000	NaN
723013	KILM	1996	07	02	0800	NaN	000	NaN
723013	KILM	1996	07	02	0900	070	003	NaN
723013	KILM	1996	07	02	0904	060	004	NaN
723013	KILM	1996	07	02	1000	NaN	000	NaN
723013	KILM	1996	07	02	1100	080	004	NaN
723013	KILM	1996	07	02	1200	100	006	NaN
723013	KILM	1996	07	02	1219	120	006	NaN
723013	KILM	1996	07	02	1300	090	006	NaN
723013	KILM	1996	07	02	1333	140	006	NaN
723013	KILM	1996	07	02	1400	120	007	NaN
723013	KILM	1996	07	02	1449	090	008	NaN
723013	KILM	1996	07	02	1500	120	007	NaN

	Yr		Mo	Da	Hr	Dir	Sus	Gust
						(Knots		)
723013	KILM	1996	07	02	1600	110	007	NaN
723013	KILM	1996	07	02	1700	100	007	NaN
723013	KILM	1996	07	02	1829	150	008	NaN
723013	KILM	1996	07	02	1839	150	009	NaN
723013	KILM	1996	07	02	1848	170	015	023
723013	KILM	1996	07	02	1900	060	005	016
723013	KILM	1996	07	02	1905	350	018	023
723013	KILM	1996	07	02	1913	310	011	025
723013	KILM	1996	07	02	1918	280	009	NaN
723013	KILM	1996	07	02	1924	200	012	NaN
723013	KILM	1996	07	02	1934	NaN	000	NaN
723013	KILM	1996	07	02	1943	NaN	004	NaN
723013	KILM	1996	07	02	2000	280	003	014
723013	KILM	1996	07	02	2009	NaN	000	NaN
723013	KILM	1996	07	02	2100	NaN	000	NaN
723013	KILM	1996	07	02	2200	NaN	000	NaN
723013	KILM	1996	07	02	2247	330	016	026
723013	KILM	1996	07	02	2300	290	020	032
723013	KILM	1996	07	02	2301	250	009	026
723013	KILM	1996	07	02	2313	NaN	000	NaN
723013	KILM	1996	07	02	2331	110	005	NaN
723013	KILM	1996	07	02	2346	130	008	NaN
723013	KILM	1996	07	03	0000	140	004	NaN
723013	KILM	1996	07	03	0041	340	008	017
723013	KILM	1996	07	03	0100	310	011	NaN
723013	KILM	1996	07	03	0103	320	007	017
723013	KILM	1996	07	03	0111	220	006	NaN
723013	KILM	1996	07	03	0121	210	006	NaN
723013	KILM	1996	07	03	0134	150	003	NaN
723013	KILM	1996	07	03	0200	170	006	NaN
723013	KILM	1996	07	03	0300	170	006	NaN
723013	KILM	1996	07	03	0400	220	004	NaN
723013	KILM	1996	07	03	0500	190	005	NaN
723013	KILM	1996	07	03	0600	NaN	000	NaN
723013	KILM	1996	07	03	0700	350	003	NaN
723013	KILM	1996	07	03	0800	280	004	NaN
723013	KILM	1996	07	03	0900	290	004	NaN
723013	KILM	1996	07	03	1000	240	005	NaN
723013	KILM	1996	07	03	1008	270	007	NaN
723013	KILM	1996	07	03	1024	270	006	NaN
723013	KILM	1996	07	03	1031	270	005	NaN
723013	KILM	1996	07	03	1045	250	004	NaN
723013	KILM	1996	07	03	1056	260	005	NaN
723013	KILM	1996	07	03	1100	260	005	NaN
723013	KILM	1996	07	03	1133	270	006	NaN
723013	KILM	1996	07	03	1200	280	006	NaN
723013	KILM	1996	07	03	1300	270	007	NaN
723013	KILM	1996	07	03	1314	280	007	NaN

		Yr	Mo	Da	Hr	Dir	Sus	Gust
						(Knots)		
723013	KILM	1996	07	03	1326	260	008	NaN
723013	KILM	1996	07	03	1334	270	009	NaN
723013	KILM	1996	07	03	1400	260	007	NaN
723013	KILM	1996	07	03	1500	280	005	NaN
723013	KILM	1996	07	03	1600	250	007	NaN
723013	KILM	1996	07	03	1700	200	006	NaN
723013	KILM	1996	07	03	1800	170	004	NaN
723013	KILM	1996	07	03	1817	200	007	NaN
723013	KILM	1996	07	03	1842	240	015	018
723013	KILM	1996	07	03	1900	230	009	NaN
723013	KILM	1996	07	03	2000	NaN	003	NaN
723013	KILM	1996	07	03	2023	240	009	022
723013	KILM	1996	07	03	2027	NaN	006	NaN
723013	KILM	1996	07	03	2033	180	005	NaN
723013	KILM	1996	07	03	2035	160	005	NaN
723013	KILM	1996	07	03	2100	NaN	000	NaN
723013	KILM	1996	07	03	2104	310	014	019
723013	KILM	1996	07	03	2111	230	012	019
723013	KILM	1996	07	03	2114	220	008	016
723013	KILM	1996	07	03	2137	NaN	004	NaN
723013	KILM	1996	07	03	2148	080	005	NaN
723013	KILM	1996	07	03	2200	NaN	000	NaN
723013	KILM	1996	07	03	2300	NaN	000	NaN
723013	KILM	1996	07	04	0000	NaN	000	NaN
723013	KILM	1996	07	04	0100	NaN	000	NaN
723013	KILM	1996	07	04	0200	NaN	000	NaN
723013	KILM	1996	07	04	0300	NaN	000	NaN
723013	KILM	1996	07	04	0400	340	005	NaN
723013	KILM	1996	07	04	0500	020	003	NaN
723013	KILM	1996	07	04	0600	020	004	NaN
723013	KILM	1996	07	04	0700	360	005	NaN
723013	KILM	1996	07	04	0800	350	006	NaN
723013	KILM	1996	07	04	0900	360	007	NaN
723013	KILM	1996	07	04	1000	350	005	NaN
723013	KILM	1996	07	04	1100	350	005	NaN
723013	KILM	1996	07	04	1200	360	006	NaN
723013	KILM	1996	07	04	1300	360	008	NaN
723013	KILM	1996	07	04	1400	360	008	NaN
723013	KILM	1996	07	04	1500	340	008	NaN
723013	KILM	1996	07	04	1600	320	009	NaN
723013	KILM	1996	07	04	1700	340	008	NaN
723013	KILM	1996	07	04	1800	290	009	NaN
723013	KILM	1996	07	04	1900	320	007	NaN
723013	KILM	1996	07	04	2000	300	008	NaN
723013	KILM	1996	07	04	2100	310	006	NaN
723013	KILM	1996	07	04	2200	260	006	NaN
723013	KILM	1996	07	04	2300	240	006	NaN
723013	KILM	1996	07	05	0000	230	003	NaN

		Yr	Mo	Da	Hr	Dir	Sus	Gust
							(Knots)	
723013	KILM	1996	07	05	0100	NaN	000	NaN
723013	KILM	1996	07	05	0200	NaN	000	NaN
723013	KILM	1996	07	05	0300	NaN	000	NaN
723013	KILM	1996	07	05	0400	NaN	000	NaN
723013	KILM	1996	07	05	0500	NaN	000	NaN
723013	KILM	1996	07	05	0600	NaN	000	NaN
723013	KILM	1996	07	05	0700	NaN	000	NaN
723013	KILM	1996	07	05	0800	NaN	000	NaN
723013	KILM	1996	07	05	0900	NaN	000	NaN
723013	KILM	1996	07	05	1000	NaN	000	NaN
723013	KILM	1996	07	05	1003	NaN	000	NaN
723013	KILM	1996	07	05	1010	NaN	000	NaN
723013	KILM	1996	07	05	1029	NaN	000	NaN
723013	KILM	1996	07	05	1100	NaN	000	NaN
723013	KILM	1996	07	05	1127	NaN	000	NaN
723013	KILM	1996	07	05	1200	NaN	000	NaN
723013	KILM	1996	07	05	1300	NaN	000	NaN
723013	KILM	1996	07	05	1400	NaN	000	NaN
723013	KILM	1996	07	05	1500	160	006	NaN
723013	KILM	1996	07	05	1600	160	008	NaN
723013	KILM	1996	07	05	1700	150	007	NaN
723013	KILM	1996	07	05	1800	140	007	NaN
723013	KILM	1996	07	05	1900	150	007	NaN
723013	KILM	1996	07	05	2000	160	010	014
723013	KILM	1996	07	05	2100	150	008	NaN
723013	KILM	1996	07	05	2200	160	007	NaN
723013	KILM	1996	07	05	2300	170	007	NaN
723013	KILM	1996	07	06	0000	130	004	NaN
723013	KILM	1996	07	06	0100	180	007	NaN
723013	KILM	1996	07	06	0200	200	003	NaN
723013	KILM	1996	07	06	0300	NaN	000	NaN
723013	KILM	1996	07	06	0400	NaN	000	NaN
723013	KILM	1996	07	06	0500	NaN	000	NaN
723013	KILM	1996	07	06	0600	NaN	000	NaN
723013	KILM	1996	07	06	0700	NaN	000	NaN
723013	KILM	1996	07	06	0800	100	004	NaN
723013	KILM	1996	07	06	0818	NaN	000	NaN
723013	KILM	1996	07	06	0848	350	003	NaN
723013	KILM	1996	07	06	0900	360	005	NaN
723013	KILM	1996	07	06	0907	360	004	Na
723013	KILM	1996	07	06	1000	350	003	NaN
723013	KILM	1996	07	06	1011	050	003	NaN
723013	KILM	1996	07	06	1100	070	003	NaN
723013	KILM	1996	07	06	1200	070	005	NaN
723013	KILM	1996	07	06	1237	NaN	000	NaN
723013	KILM	1996	07	06	1300	080	006	NaN
723013	KILM	1996	07	06	1310	070	007	NaN
723013	KILM	1996	07	06	1319	080	006	NaN

		Yr	Mo	Da	Hr	Dir	Sus	Gust
						(Knots)		
723013	KILM	1996	07	06	1400	050	003	NaN
723013	KILM	1996	07	06	1412	070	004	NaN
723013	KILM	1996	07	06	1500	090	006	NaN
723013	KILM	1996	07	06	1600	NaN	000	NaN
723013	KILM	1996	07	06	1634	010	006	NaN
723013	KILM	1996	07	06	1700	150	004	NaN
723013	KILM	1996	07	06	1731	110	006	NaN
723013	KILM	1996	07	06	1800	140	005	NaN
723013	KILM	1996	07	06	1900	NaN	003	NaN
723013	KILM	1996	07	06	1903	110	005	NaN
723013	KILM	1996	07	06	1931	100	004	NaN
723013	KILM	1996	07	06	2000	NaN	000	NaN
723013	KILM	1996	07	06	2100	150	005	NaN
723013	KILM	1996	07	06	2130	180	006	NaN
723013	KILM	1996	07	06	2200	190	003	NaN
723013	KILM	1996	07	06	2235	130	007	NaN
723013	KILM	1996	07	06	2300	090	007	NaN
723013	KILM	1996	07	06	2316	140	005	NaN
723013	KILM	1996	07	07	0000	150	006	NaN
723013	KILM	1996	07	07	0003	170	005	NaN
723013	KILM	1996	07	07	0021	170	006	NaN
723013	KILM	1996	07	07	0100	190	003	NaN
723013	KILM	1996	07	07	0200	190	005	NaN
723013	KILM	1996	07	07	0300	220	006	NaN
723013	KILM	1996	07	07	0400	230	007	NaN
723013	KILM	1996	07	07	0500	220	005	NaN
723013	KILM	1996	07	07	0600	230	004	NaN
723013	KILM	1996	07	07	0700	250	005	NaN
723013	KILM	1996	07	07	0800	250	006	NaN
723013	KILM	1996	07	07	0900	250	004	NaN
723013	KILM	1996	07	07	1000	260	004	NaN
723013	KILM	1996	07	07	1032	260	003	NaN
723013	KILM	1996	07	07	1100	240	004	NaN
723013	KILM	1996	07	07	1110	250	005	NaN
723013	KILM	1996	07	07	1122	240	006	NaN
723013	KILM	1996	07	07	1200	270	005	NaN
723013	KILM	1996	07	07	1213	280	005	NaN
723013	KILM	1996	07	07	1300	280	003	NaN
723013	KILM	1996	07	07	1400	NaN	000	NaN
723013	KILM	1996	07	07	1500	270	004	NaN
723013	KILM	1996	07	07	1600	230	004	NaN
723013	KILM	1996	07	07	1700	NaN	003	NaN
723013	KILM	1996	07	07	1800	150	007	NaN
723013	KILM	1996	07	07	1900	150	009	NaN
723013	KILM	1996	07	07	2000	210	011	NaN
723013	KILM	1996	07	07	2100	190	007	NaN
723013	KILM	1996	07	07	2200	200	012	NaN
723013	KILM	1996	07	07	2300	220	009	NaN

		Yr	Mo	Da	Hr	Dir	Sus	Gust
							(Knots)	
723013	KILM	1996	07	08	0000	220	008	NaN
723013	KILM	1996	07	08	0100	200	009	NaN
723013	KILM	1996	07	08	0200	200	007	NaN
723013	KILM	1996	07	08	0300	200	007	NaN
723013	KILM	1996	07	08	0400	190	005	NaN
723013	KILM	1996	07	08	0500	200	004	NaN
723013	KILM	1996	07	08	0600	210	006	NaN
723013	KILM	1996	07	08	0700	210	007	NaN
723013	KILM	1996	07	08	0800	210	005	NaN
723013	KILM	1996	07	08	0900	230	007	NaN
723013	KILM	1996	07	08	1000	210	004	NaN
723013	KILM	1996	07	08	1100	210	008	NaN
723013	KILM	1996	07	08	1200	220	009	NaN
723013	KILM	1996	07	08	1300	230	009	NaN
723013	KILM	1996	07	08	1400	250	006	NaN
723013	KILM	1996	07	08	1500	230	007	NaN
723013	KILM	1996	07	08	1600	230	005	NaN
723013	KILM	1996	07	08	1700	200	009	NaN
723013	KILM	1996	07	08	1800	230	008	NaN
723013	KILM	1996	07	08	1900	220	007	NaN
723013	KILM	1996	07	08	2000	220	009	NaN
723013	KILM	1996	07	08	2100	220	011	NaN
723013	KILM	1996	07	08	2200	200	011	NaN
723013	KILM	1996	07	08	2300	210	013	NaN
723013	KILM	1996	07	09	0000	210	011	NaN
723013	KILM	1996	07	09	0100	230	012	019
723013	KILM	1996	07	09	0200	210	008	NaN
723013	KILM	1996	07	09	0300	220	008	NaN
723013	KILM	1996	07	09	0400	210	008	NaN
723013	KILM	1996	07	09	0500	210	010	NaN
723013	KILM	1996	07	09	0600	200	009	NaN
723013	KILM	1996	07	09	0700	230	007	NaN
723013	KILM	1996	07	09	0800	240	011	NaN
723013	KILM	1996	07	09	0900	230	009	NaN
723013	KILM	1996	07	09	1000	240	011	018
723013	KILM	1996	07	09	1100	250	010	NaN
723013	KILM	1996	07	09	1200	240	010	NaN
723013	KILM	1996	07	09	1300	240	012	018
723013	KILM	1996	07	09	1400	260	010	NaN
723013	KILM	1996	07	09	1500	250	010	NaN
723013	KILM	1996	07	09	1600	250	009	NaN
723013	KILM	1996	07	09	1700	250	010	NaN
723013	KILM	1996	07	09	1800	210	010	NaN
723013	KILM	1996	07	09	2000	230	012	016
723013	KILM	1996	07	09	2100	190	014	NaN
723013	KILM	1996	07	09	2200	180	014	NaN
723013	KILM	1996	07	09	2206	200	013	NaN

		Yr	Mo	Da	Hr	Dir	Sus	Gust
							(Knots)	
723013	KILM	1996	07	09	2300	200	015	NaN
723013	KILM	1996	07	09	2303	210	013	019
723013	KILM	1996	07	10	0000	210	011	NaN
723013	KILM	1996	07	10	0100	220	009	NaN
723013	KILM	1996	07	10	0200	200	009	NaN
723013	KILM	1996	07	10	0300	200	008	NaN
723013	KILM	1996	07	10	0400	200	008	NaN
723013	KILM	1996	07	10	0600	190	007	NaN
723013	KILM	1996	07	10	0642	200	007	NaN
723013	KILM	1996	07	10	0700	220	006	NaN
723013	KILM	1996	07	10	0800	210	003	NaN
723013	KILM	1996	07	10	0900	210	005	NaN
723013	KILM	1996	07	10	0908	210	006	NaN
723013	KILM	1996	07	10	0919	210	007	NaN
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723013	KILM	1996	07	10	1000	210	007	NaN
723013	KILM	1996	07	10	1006	210	005	NaN
723013	KILM	1996	07	10	1100	230	005	NaN
723013	KILM	1996	07	10	1103	240	009	NaN
723013	KILM	1996	07	10	1108	240	008	NaN
723013	KILM	1996	07	10	1122	210	005	NaN
723013	KILM	1996	07	10	1140	230	003	NaN
723013	KILM	1996	07	10	1200	300	005	NaN
723013	KILM	1996	07	10	1204	290	004	NaN
723013	KILM	1996	07	10	1249	NaN	000	NaN
723013	KILM	1996	07	10	1300	NaN	003	NaN
723013	KILM	1996	07	10	1319	330	006	NaN
723013	KILM	1996	07	10	1327	320	006	NaN
723013	KILM	1996	07	10	1345	360	004	NaN
723013	KILM	1996	07	10	1400	NaN	000	NaN
723013	KILM	1996	07	10	1407	NaN	000	NaN
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723013	KILM	1996	07	10	1716	090	007	NaN
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723013	KILM	1996	07	10	2035	070	009	NaN
723013	KILM	1996	07	10	2100	080	010	NaN
723013	KILM	1996	07	10	2200	090	011	017
723013	KILM	1996	07	10	2228	090	012	019
723013	KILM	1996	07	10	2300	080	016	NaN
723013	KILM	1996	07	11	0000	070	010	NaN
723013	KILM	1996	07	11	0100	040	007	NaN
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		Yr	Mo	Da	Hr	Dir	Sus	Gust
							(Knots)	
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723013	KILM	1996	07	11	0226	030	008	NaN
723013	KILM	1996	07	11	0243	040	008	NaN
723013	KILM	1996	07	11	0300	060	008	NaN
723013	KILM	1996	07	11	0337	040	005	NaN
723013	KILM	1996	07	11	0400	050	007	NaN
723013	KILM	1996	07	11	0410	050	006	NaN
723013	KILM	1996	07	11	0445	030	008	NaN
723013	KILM	1996	07	11	0500	040	007	NaN
723013	KILM	1996	07	11	0528	050	007	NaN
723013	KILM	1996	07	11	0600	040	007	NaN
723013	KILM	1996	07	11	0700	020	007	NaN
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723013	KILM	1996	07	11	0737	030	010	NaN
723013	KILM	1996	07	11	0800	020	010	NaN
723013	KILM	1996	07	11	0900	030	011	NaN
723013	KILM	1996	07	11	0916	030	011	NaN
723013	KILM	1996	07	11	0930	040	010	NaN
723013	KILM	1996	07	11	0947	040	009	NaN
723013	KILM	1996	07	11	1000	040	011	NaN
723013	KILM	1996	07	11	1030	050	012	NaN
723013	KILM	1996	07	11	1100	050	012	NaN
723013	KILM	1996	07	11	1107	050	013	NaN
723013	KILM	1996	07	11	1200	050	008	NaN
723013	KILM	1996	07	11	1300	050	009	NaN
723013	KILM	1996	07	11	1308	060	008	NaN
723013	KILM	1996	07	11	1400	080	013	020
723013	KILM	1996	07	11	1418	070	015	027
723013	KILM	1996	07	11	1500	060	015	026
723013	KILM	1996	07	11	1600	060	018	025
723013	KILM	1996	07	11	1700	060	015	023
723013	KILM	1996	07	11	1800	070	020	026
723013	KILM	1996	07	11	1900	060	016	023
723013	KILM	1996	07	11	2000	060	018	024
723013	KILM	1996	07	11	2100	060	015	022
723013	KILM	1996	07	11	2200	060	014	021
723013	KILM	1996	07	11	2300	050	013	NaN
723013	KILM	1996	07	12	0000	030	012	NaN
723013	KILM	1996	07	12	0017	040	009	NaN
723013	KILM	1996	07	12	0100	040	009	NaN
723013	KILM	1996	07	12	0200	040	008	NaN
723013	KILM	1996	07	12	0214	030	011	NaN
723013	KILM	1996	07	12	0239	040	012	NaN
723013	KILM	1996	07	12	0300	030	012	NaN
723013	KILM	1996	07	12	0305	040	010	NaN
723013	KILM	1996	07	12	0400	040	010	NaN

		Yr	Mo	Da	Hr	Dir	Sus	Gust
							(Knots)	
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723013	KILM	1996	07	12	0428	040	008	NaN
723013	KILM	1996	07	12	0500	070	007	NaN
723013	KILM	1996	07	12	0502	070	011	018
723013	KILM	1996	07	12	0513	090	013	018
723013	KILM	1996	07	12	0539	110	010	NaN
723013	KILM	1996	07	12	0547	130	011	015
723013	KILM	1996	07	12	0556	080	009	NaN
723013	KILM	1996	07	12	0600	060	012	015
723013	KILM	1996	07	12	0700	050	008	NaN
723013	KILM	1996	07	12	0800	060	010	NaN
723013	KILM	1996	07	12	0900	050	008	NaN
723013	KILM	1996	07	12	1000	070	013	020
723013	KILM	1996	07	12	1100	060	018	023
723013	KILM	1996	07	12	1106	070	013	022
723013	KILM	1996	07	12	1113	070	013	022
723013	KILM	1996	07	12	1200	070	011	018
723013	KILM	1996	07	12	1300	060	010	018
723013	KILM	1996	07	12	1303	080	013	021
723013	KILM	1996	07	12	1400	080	018	024
723013	KILM	1996	07	12	1415	080	020	034
723013	KILM	1996	07	12	1441	070	019	031
723013	KILM	1996	07	12	1500	070	024	030
723013	KILM	1996	07	12	1528	070	025	033
723013	KILM	1996	07	12	1535	060	024	034
723013	KILM	1996	07	12	1545	060	022	034
723013	KILM	1996	07	12	1600	070	036	045
723013	KILM	1996	07	12	1603	060	027	043
723013	KILM	1996	07	12	1628	050	034	053
723013	KILM	1996	07	12	1700	050	039	050
723013	KILM	1996	07	12	1748	050	039	055
723013	KILM	1996	07	12	1800	060	041	055
723013	KILM	1996	07	12	1819	040	042	057
723013	KILM	1996	07	12	1831	040	034	059
723013	KILM	1996	07	12	1900	040	043	057
723013	KILM	1996	07	12	1942	360	032	043
723013	KILM	1996	07	12	2000	340	019	039
723013	KILM	1996	07	12	2004	330	027	035
723013	KILM	1996	07	12	2033	300	030	043
723013	KILM	1996	07	12	2100	280	035	044
723013	KILM	1996	07	12	2105	290	035	044
723013	KILM	1996	07	12	2113	270	038	049
723013	KILM	1996	07	12	2130	260	033	047
723013	KILM	1996	07	12	2200	260	026	038
723013	KILM	1996	07	12	2217	240	028	036
723013	KILM	1996	07	12	2221	240	027	036
723013	KILM	1996	07	12	2245	230	024	043

		Yr	Mo	Da	Hr	Dir	Sus	Gust
							(Knots)	
723013	KILM	1996	07	12	2300	230	032	046
723013	KILM	1996	07	12	2311	240	030	043
723013	KILM	1996	07	12	2322	240	032	040
723013	KILM	1996	07	12	2326	230	029	040
723013	KILM	1996	07	12	2349	230	029	035
723013	KILM	1996	07	13	0000	230	023	034
723013	KILM	1996	07	13	0022	240	024	036
723013	KILM	1996	07	13	0037	230	027	032
723013	KILM	1996	07	13	0100	220	023	036
723013	KILM	1996	07	13	0123	230	025	030
723013	KILM	1996	07	13	0200	220	023	032
723013	KILM	1996	07	13	0225	230	019	032
723013	KILM	1996	07	13	0300	220	020	025
723013	KILM	1996	07	13	0400	230	018	023
723013	KILM	1996	07	13	0500	230	019	023
723013	KILM	1996	07	13	0600	230	014	023
723013	KILM	1996	07	13	0619	240	014	019
723013	KILM	1996	07	13	0646	230	011	NaN
723013	KILM	1996	07	13	0700	230	012	NaN
723013	KILM	1996	07	13	0800	250	011	NaN
723013	KILM	1996	07	13	1000	220	009	NaN
723013	KILM	1996	07	13	1100	210	007	NaN
723013	KILM	1996	07	13	1300	220	010	NaN
723013	KILM	1996	07	13	1400	220	011	NaN
723013	KILM	1996	07	13	1500	230	014	NaN
723013	KILM	1996	07	13	1600	240	012	NaN
723013	KILM	1996	07	13	1700	220	012	NaN
723013	KILM	1996	07	13	1800	210	013	NaN
723013	KILM	1996	07	13	1900	220	013	NaN
723013	KILM	1996	07	13	2000	210	013	NaN
723013	KILM	1996	07	13	2100	210	008	NaN
723013	KILM	1996	07	13	2200	200	010	NaN
723013	KILM	1996	07	13	2300	190	011	NaN
723013	KILM	1996	07	14	0000	180	011	NaN
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723013	KILM	1996	07	14	0200	200	008	NaN
723013	KILM	1996	07	14	0300	190	006	NaN
723013	KILM	1996	07	14	0400	210	007	NaN
723013	KILM	1996	07	14	0500	200	005	NaN
723013	KILM	1996	07	14	0600	180	005	NaN
723013	KILM	1996	07	14	0615	190	005	NaN
723013	KILM	1996	07	14	0643	190	006	NaN
723013	KILM	1996	07	14	0700	200	007	NaN
723013	KILM	1996	07	14	0726	200	007	NaN
723013	KILM	1996	07	14	0800	200	006	NaN
723013	KILM	1996	07	14	0817	190	005	NaN
723013	KILM	1996	07	14	0824	190	004	NaN

		Yr	Mo	Da	Hr	Dir	Sus	Gust
							(Knots)	
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723013	KILM	1996	07	14	0900	210	006	NaN
723013	KILM	1996	07	14	0906	210	006	NaN
723013	KILM	1996	07	14	1000	210	005	NaN
723013	KILM	1996	07	14	1026	200	003	NaN
723013	KILM	1996	07	14	1100	190	004	NaN
723013	KILM	1996	07	14	1200	200	006	NaN
723013	KILM	1996	07	14	1300	210	007	NaN
723013	KILM	1996	07	14	1400	200	007	NaN
723013	KILM	1996	07	14	1422	210	006	NaN
723013	KILM	1996	07	14	1438	210	005	NaN
723013	KILM	1996	07	14	1500	210	006	NaN
723013	KILM	1996	07	14	1600	210	009	NaN
723013	KILM	1996	07	14	1624	210	010	NaN
723013	KILM	1996	07	14	1700	200	010	NaN
723013	KILM	1996	07	14	1800	220	008	NaN
723013	KILM	1996	07	14	1829	280	008	019
723013	KILM	1996	07	14	1848	230	003	NaN
723013	KILM	1996	07	14	1900	220	003	NaN
723013	KILM	1996	07	14	1920	220	008	NaN
723013	KILM	1996	07	14	1922	180	012	020
723013	KILM	1996	07	14	1929	170	013	020
723013	KILM	1996	07	14	1931	170	011	020
723013	KILM	1996	07	14	1938	160	009	NaN
723013	KILM	1996	07	14	2000	190	005	NaN
723013	KILM	1996	07	14	2100	150	006	NaN
723013	KILM	1996	07	14	2200	160	007	NaN
723013	KILM	1996	07	14	2300	180	008	NaN
723013	KILM	1996	07	14	2303	180	008	NaN
723013	KILM	1996	07	14	2316	180	009	NaN
723013	KILM	1996	07	14	2324	170	009	NaN
723013	KILM	1996	07	14	2331	180	010	NaN
723013	KILM	1996	07	15	0100	190	009	NaN
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723013	KILM	1996	07	15	0138	190	008	NaN
723013	KILM	1996	07	15	0200	190	009	NaN
723013	KILM	1996	07	15	0238	200	008	NaN
723013	KILM	1996	07	15	0300	190	008	NaN
723013	KILM	1996	07	15	0339	190	007	NaN
723013	KILM	1996	07	15	0400	190	007	NaN
723013	KILM	1996	07	15	0446	190	009	NaN
723013	KILM	1996	07	15	0500	200	009	017
723013	KILM	1996	07	15	0600	190	011	NaN
723013	KILM	1996	07	15	0700	190	009	NaN
723013	KILM	1996	07	15	0800	200	013	NaN
723013	KILM	1996	07	15	0900	190	011	NaN
723013	KILM	1996	07	15	1000	190	011	NaN

		Yr	Mo	Da	Hr	Dir	Sus	Gust
							(Knots)	
723013	KILM	1996	07	15	1100	190	011	NaN
723013	KILM	1996	07	15	1200	200	011	NaN
723013	KILM	1996	07	15	1223	200	010	NaN
723013	KILM	1996	07	15	1300	200	013	NaN
723013	KILM	1996	07	15	1321	200	014	019
723013	KILM	1996	07	15	1344	210	013	NaN
723013	KILM	1996	07	15	1400	200	017	022
723013	KILM	1996	07	15	1429	200	013	020
723013	KILM	1996	07	15	1500	200	016	021
723013	KILM	1996	07	15	1517	210	015	020
723013	KILM	1996	07	15	1530	220	016	020
723013	KILM	1996	07	15	1539	200	015	023
723013	KILM	1996	07	15	1546	210	017	022
723013	KILM	1996	07	15	1600	200	015	020
723013	KILM	1996	07	15	1629	210	017	023
723013	KILM	1996	07	15	1700	220	011	022
723013	KILM	1996	07	15	1717	200	014	020
723013	KILM	1996	07	15	1800	200	015	NaN
723013	KILM	1996	07	15	1847	200	015	021
723013	KILM	1996	07	15	1900	200	017	025
723013	KILM	1996	07	15	1906	210	018	023
723013	KILM	1996	07	15	1935	200	015	019
723013	KILM	1996	07	15	2000	200	015	021
723013	KILM	1996	07	15	2004	210	017	023
723013	KILM	1996	07	15	2024	210	014	022
723013	KILM	1996	07	15	2038	200	011	022
723013	KILM	1996	07	15	2100	190	017	022
723013	KILM	1996	07	15	2200	210	013	021
723013	KILM	1996	07	15	2203	210	011	021
723013	KILM	1996	07	15	2300	200	010	NaN
723013	KILM	1996	09	01	0000	360	005	NaN
723013	KILM	1996	09	01	0100	010	003	NaN
723013	KILM	1996	09	01	0200	010	003	NaN
723013	KILM	1996	09	01	0300	340	005	NaN
723013	KILM	1996	09	01	0400	360	006	NaN
723013	KILM	1996	09	01	0500	350	004	NaN

Hurricane Fran

		Yr	Mo	Da	Hr	Dir	Sus	Gust
							(Knots)	
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723013	KILM	1996	09	01	0700	010	009	NaN
723013	KILM	1996	09	01	0800	010	009	NaN
723013	KILM	1996	09	01	0900	020	007	NaN
723013	KILM	1996	09	01	1000	020	008	NaN
723013	KILM	1996	09	01	1100	020	007	NaN
723013	KILM	1996	09	01	1200	020	006	NaN

		Yr	Mo	Da	Hr	Dir	Sus	Gust
						(Knots)		
723013	KILM	1996	09	01	1300	030	009	NaN
723013	KILM	1996	09	01	1400	030	009	NaN
723013	KILM	1996	09	01	1500	020	010	NaN
723013	KILM	1996	09	01	1600	020	010	NaN
723013	KILM	1996	09	01	1700	040	006	014
723013	KILM	1996	09	01	1800	050	007	NaN
723013	KILM	1996	09	01	1900	NaN	000	NaN
723013	KILM	1996	09	01	2000	110	007	NaN
723013	KILM	1996	09	01	2100	NaN	006	NaN
723013	KILM	1996	09	01	2200	120	004	NaN
723013	KILM	1996	09	01	2300	150	004	NaN
723013	KILM	1996	09	02	0000	120	004	NaN
723013	KILM	1996	09	02	0100	NaN	000	NaN
723013	KILM	1996	09	02	0200	040	003	NaN
723013	KILM	1996	09	02	0300	NaN	000	NaN
723013	KILM	1996	09	02	0400	NaN	000	NaN
723013	KILM	1996	09	02	0500	NaN	000	NaN
723013	KILM	1996	09	02	0600	NaN	000	NaN
723013	KILM	1996	09	02	0700	NaN	000	NaN
723013	KILM	1996	09	02	0800	NaN	000	NaN
723013	KILM	1996	09	02	0900	NaN	000	NaN
723013	KILM	1996	09	02	0904	NaN	000	NaN
723013	KILM	1996	09	02	0924	030	005	NaN
723013	KILM	1996	09	02	1000	040	005	NaN
723013	KILM	1996	09	02	1100	050	003	NaN
723013	KILM	1996	09	02	1200	NaN	000	NaN
723013	KILM	1996	09	02	1300	050	003	NaN
723013	KILM	1996	09	02	1400	110	009	NaN
723013	KILM	1996	09	02	1500	120	006	NaN
723013	KILM	1996	09	02	1600	110	008	NaN
723013	KILM	1996	09	02	1700	100	010	NaN
723013	KILM	1996	09	02	1800	120	008	NaN
723013	KILM	1996	09	02	1900	110	005	NaN
723013	KILM	1996	09	02	2000	110	005	NaN
723013	KILM	1996	09	02	2100	120	012	NaN
723013	KILM	1996	09	02	2200	100	006	NaN
723013	KILM	1996	09	02	2300	110	006	NaN
723013	KILM	1996	09	03	0000	110	005	NaN
723013	KILM	1996	09	03	0100	140	007	NaN
723013	KILM	1996	09	03	0200	130	006	NaN
723013	KILM	1996	09	03	0300	130	008	NaN
723013	KILM	1996	09	03	0400	130	008	NaN
723013	KILM	1996	09	03	0500	120	009	NaN
723013	KILM	1996	09	03	0600	120	008	NaN
723013	KILM	1996	09	03	0700	130	008	NaN
723013	KILM	1996	09	03	0800	150	011	016
723013	KILM	1996	09	03	0900	150	007	NaN
723013	KILM	1996	09	03	0922	170	008	018

		Yr	Mo	Da	Hr	Dir	Sus	Gust
							(Knots)	
723013	KILM	1996	09	03	0929	150	006	NaN
723013	KILM	1996	09	03	1000	110	007	NaN
723013	KILM	1996	09	03	1100	120	007	NaN
723013	KILM	1996	09	03	1200	140	007	NaN
723013	KILM	1996	09	03	1211	150	012	019
723013	KILM	1996	09	03	1223	130	009	018
723013	KILM	1996	09	03	1230	130	007	NaN
723013	KILM	1996	09	03	1300	110	008	NaN
723013	KILM	1996	09	03	1316	130	013	020
723013	KILM	1996	09	03	1320	140	012	020
723013	KILM	1996	09	03	1324	140	011	020
723013	KILM	1996	09	03	1332	130	013	018
723013	KILM	1996	09	03	1335	130	009	018
723013	KILM	1996	09	03	1340	120	006	018
723013	KILM	1996	09	03	1348	130	010	NaN
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723013	KILM	1996	09	03	1526	150	007	NaN
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723013	KILM	1996	09	03	1531	140	007	NaN
723013	KILM	1996	09	03	1538	140	007	NaN
723013	KILM	1996	09	03	1541	140	007	NaN
723013	KILM	1996	09	03	1543	130	005	NaN
723013	KILM	1996	09	03	1556	140	006	NaN
723013	KILM	1996	09	03	1600	NaN	004	NaN
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723013	KILM	1996	09	03	1610	120	005	NaN
723013	KILM	1996	09	03	1616	NaN	005	NaN
723013	KILM	1996	09	03	1618	110	006	NaN
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723013	KILM	1996	09	03	2105	150	008	NaN
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723013	KILM	1996	09	04	0000	170	003	NaN

		Yr	Mo	Da	Hr	Dir	Sus	Gust
						(Knots)		
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723013	KILM	1996	09	04	0200	NaN	000	NaN
723013	KILM	1996	09	04	0300	NaN	000	NaN
723013	KILM	1996	09	04	0400	NaN	000	NaN
723013	KILM	1996	09	03	0200	130	006	NaN
723013	KILM	1996	09	04	0500	330	004	NaN
723013	KILM	1996	09	04	0525	NaN	000	NaN
723013	KILM	1996	09	04	0539	NaN	003	NaN
723013	KILM	1996	09	04	0546	NaN	000	NaN
723013	KILM	1996	09	04	0600	NaN	000	NaN
723013	KILM	1996	09	04	0648	NaN	000	NaN
723013	KILM	1996	09	04	0700	NaN	000	NaN
723013	KILM	1996	09	04	0743	NaN	003	NaN
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723013	KILM	1996	09	04	0829	NaN	000	NaN
723013	KILM	1996	09	04	0842	070	007	NaN
723013	KILM	1996	09	04	0900	080	004	NaN
723013	KILM	1996	09	04	0903	060	004	NaN
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723013	KILM	1996	09	04	1235	040	007	NaN
723013	KILM	1996	09	04	1300	040	007	NaN
723013	KILM	1996	09	04	1325	040	008	NaN
723013	KILM	1996	09	04	1400	070	005	NaN
723013	KILM	1996	09	04	1500	060	006	NaN
723013	KILM	1996	09	04	1541	060	006	NaN
723013	KILM	1996	09	04	1600	040	007	NaN
723013	KILM	1996	09	04	1617	040	005	NaN
723013	KILM	1996	09	04	1626	060	007	NaN
723013	KILM	1996	09	04	1700	NaN	003	NaN
723013	KILM	1996	09	04	1727	100	008	NaN
723013	KILM	1996	09	04	1800	090	007	NaN
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723013	KILM	1996	09	04	1820	070	007	NaN
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723013	KILM	1996	09	04	1911	070	008	NaN
723013	KILM	1996	09	04	1927	080	012	016
723013	KILM	1996	09	04	2000	080	010	016
723013	KILM	1996	09	04	2031	080	007	NaN
723013	KILM	1996	09	04	2100	NaN	004	NaN
723013	KILM	1996	09	04	2119	NaN	000	NaN
723013	KILM	1996	09	04	2129	070	004	NaN
723013	KILM	1996	09	04	2138	060	005	NaN
723013	KILM	1996	09	04	2200	040	003	NaN

		Yr	Mo	Da	Hr	Dir	Sus	Gust
						(Knots)		
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723013	KILM	1996	09	05	0100	060	003	NaN
723013	KILM	1996	09	05	0200	010	007	NaN
723013	KILM	1996	09	05	0211	020	006	NaN
723013	KILM	1996	09	05	0237	020	007	NaN
723013	KILM	1996	09	05	0300	020	008	NaN
723013	KILM	1996	09	05	0400	020	008	NaN
723013	KILM	1996	09	05	0411	030	009	NaN
723013	KILM	1996	09	05	0428	030	008	NaN
723013	KILM	1996	09	05	0500	020	008	NaN
723013	KILM	1996	09	05	0600	030	009	NaN
723013	KILM	1996	09	05	0700	030	009	NaN
723013	KILM	1996	09	05	0732	030	010	NaN
723013	KILM	1996	09	05	0800	040	010	NaN
723013	KILM	1996	09	05	0802	040	014	NaN
723013	KILM	1996	09	05	0806	030	012	NaN
723013	KILM	1996	09	05	0810	040	011	NaN
723013	KILM	1996	09	05	0818	040	010	NaN
723013	KILM	1996	09	05	0840	030	010	NaN
723013	KILM	1996	09	05	0848	020	009	NaN
723013	KILM	1996	09	05	0900	040	009	NaN
723013	KILM	1996	09	05	0913	030	010	NaN
723013	KILM	1996	09	05	0922	030	012	NaN
723013	KILM	1996	09	05	0924	030	012	NaN
723013	KILM	1996	09	05	0938	020	010	NaN
723013	KILM	1996	09	05	1000	030	010	NaN
723013	KILM	1996	09	05	1023	040	012	NaN
723013	KILM	1996	09	05	1100	040	010	NaN
723013	KILM	1996	09	05	1200	040	012	NaN
723013	KILM	1996	09	05	1219	040	013	NaN
723013	KILM	1996	09	05	1300	040	014	NaN
723013	KILM	1996	09	05	1327	030	015	022
723013	KILM	1996	09	05	1400	040	015	021
723013	KILM	1996	09	05	1500	050	016	023
723013	KILM	1996	09	05	1600	030	020	026
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723013	KILM	1996	09	05	1745	040	023	031
723013	KILM	1996	09	05	1800	030	025	030
723013	KILM	1996	09	05	1815	030	024	034
723013	KILM	1996	09	05	1831	030	026	033
723013	KILM	1996	09	05	1900	030	027	036
723013	KILM	1996	09	05	1901	030	027	036
723013	KILM	1996	09	05	1906	030	034	041
723013	KILM	1996	09	05	1912	040	028	041
723013	KILM	1996	09	05	1919	030	028	044
723013	KILM	1996	09	05	1923	030	028	042
723013	KILM	1996	09	05	1931	030	033	038

		Yr	Mo	Da	Hr	Dir	Sus	Gust
						(Knots)		
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723013	KILM	1996	09	05	1948	030	033	044
723013	KILM	1996	09	05	2000	040	029	047
723013	KILM	1996	09	05	2003	060	033	044
723013	KILM	1996	09	05	2008	050	025	044
723013	KILM	1996	09	05	2011	050	026	043
723013	KILM	1996	09	05	2020	060	035	051
723013	KILM	1996	09	05	2030	050	033	051
723013	KILM	1996	09	05	2032	060	035	051
723013	KILM	1996	09	05	2039	060	028	051
723013	KILM	1996	09	05	2045	060	028	048
723013	KILM	1996	09	05	2047	060	026	040
723013	KILM	1996	09	05	2129	070	027	047
723013	KILM	1996	09	05	2131	060	025	047
723013	KILM	1996	09	05	2134	050	027	045
723013	KILM	1996	09	05	2136	060	028	043
723013	KILM	1996	09	05	2145	060	034	046
723013	KILM	1996	09	05	2200	050	032	043
723013	KILM	1996	09	05	2207	050	033	049
723013	KILM	1996	09	05	2214	050	038	050
723013	KILM	1996	09	05	2240	060	034	060
723013	KILM	1996	09	05	2300	060	048	061
723013	KILM	1996	09	05	2303	060	043	061
723013	KILM	1996	09	05	2311	060	039	064
723013	KILM	1996	09	05	2318	060	040	057
723013	KILM	1996	09	05	2325	060	042	059
723013	KILM	1996	09	05	2345	060	044	068
723013	KILM	1996	09	06	0000	070	051	070
723013	KILM	1996	09	06	0003	060	048	065
723013	KILM	1996	09	06	0046	070	046	068
723013	KILM	1996	09	06	0100	090	051	075
723013	KILM	1996	09	06	0101	090	043	074
723013	KILM	1996	09	06	0125	110	035	056
723013	KILM	1996	09	06	0134	120	024	042
723013	KILM	1996	09	06	0140	140	027	042
723013	KILM	1996	09	06	0200	130	033	049
723013	KILM	1996	09	06	0218	140	030	046
723013	KILM	1996	09	06	0300	170	034	046
723013	KILM	1996	09	06	0346	180	032	039
723013	KILM	1996	09	06	0400	180	033	046
723013	KILM	1996	09	06	0427	190	026	044
723013	KILM	1996	09	06	0500	190	034	049
723013	KILM	1996	09	06	0518	190	031	039
723013	KILM	1996	09	06	0600	200	029	049
723013	KILM	1996	09	06	0648	210	029	043
723013	KILM	1996	09	06	0700	200	029	039
723013	KILM	1996	09	06	0800	200	033	043
723013	KILM	1996	09	06	0900	210	029	041

		Yr	Mo	Da	Hr	Dir	Sus	Gust
							(Knots)	
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723013	KILM	1996	09	06	1000	210	025	039
723013	KILM	1996	09	06	1100	210	021	031
723013	KILM	1996	09	06	1500	210	015	027
723013	KILM	1996	09	06	1600	220	022	034
723013	KILM	1996	09	06	1700	210	023	031
723013	KILM	1996	09	06	1800	210	019	025
723013	KILM	1996	09	06	1900	190	018	024
723013	KILM	1996	09	06	2000	210	015	021
723013	KILM	1996	09	06	2100	190	017	021
723013	KILM	1996	09	06	2200	190	013	021
723013	KILM	1996	09	06	2300	200	014	021
723013	KILM	1996	09	07	0000	200	009	017
723013	KILM	1996	09	07	0100	200	009	NaN
723013	KILM	1996	09	07	0200	210	010	NaN
723013	KILM	1996	09	07	0300	190	009	NaN
723013	KILM	1996	09	07	0400	190	010	NaN
723013	KILM	1996	09	07	0500	190	010	NaN
723013	KILM	1996	09	07	0600	200	008	NaN
723013	KILM	1996	09	07	0700	200	009	NaN
723013	KILM	1996	09	07	0800	190	005	NaN
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723013	KILM	1996	09	07	1000	190	006	NaN
723013	KILM	1996	09	07	1100	190	007	NaN
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723013	KILM	1996	09	07	1235	210	010	NaN
723013	KILM	1996	09	07	1300	220	009	NaN
723013	KILM	1996	09	07	1400	240	008	NaN
723013	KILM	1996	09	07	1500	220	006	014
723013	KILM	1996	09	07	1600	190	009	NaN
723013	KILM	1996	09	07	1700	190	010	NaN
723013	KILM	1996	09	07	1800	190	015	019
723013	KILM	1996	09	07	1900	180	011	NaN
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723013	KILM	1996	09	07	2104	170	011	NaN
723013	KILM	1996	09	07	2121	180	012	NaN
723013	KILM	1996	09	07	2200	200	008	NaN
723013	KILM	1996	09	07	2300	210	006	NaN
723013	KILM	1996	09	07	2309	230	008	NaN
723013	KILM	1996	09	07	2343	220	003	NaN
723013	KILM	1996	09	08	0000	190	005	NaN
723013	KILM	1996	09	08	0100	180	005	NaN
723013	KILM	1996	09	08	0200	180	006	NaN
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723013	KILM	1996	09	08	0329	190	006	NaN
723013	KILM	1996	09	08	0400	200	006	NaN
723013	KILM	1996	09	08	0500	190	005	NaN
723013	KILM	1996	09	08	0600	210	006	NaN

		Yr	Mo	Da	Hr	Dir	Sus	Gust
						(Knots)		
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723013	KILM	1996	09	08	0900	170	003	NaN
723013	KILM	1996	09	08	0935	170	003	NaN
723013	KILM	1996	09	08	0942	160	004	NaN
723013	KILM	1996	09	08	1000	170	004	NaN
723013	KILM	1996	09	08	1010	NaN	000	NaN
723013	KILM	1996	09	08	1019	NaN	000	NaN
723013	KILM	1996	09	08	1029	NaN	000	NaN
723013	KILM	1996	09	08	1100	NaN	000	NaN
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723013	KILM	1996	09	08	1200	NaN	000	NaN
723013	KILM	1996	09	08	1203	NaN	000	NaN
723013	KILM	1996	09	08	1215	NaN	000	NaN
723013	KILM	1996	09	08	1243	200	005	NaN
723013	KILM	1996	09	08	1300	210	006	NaN
723013	KILM	1996	09	08	1348	230	007	NaN
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723013	KILM	1996	09	08	1500	250	004	NaN
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723013	KILM	1996	09	08	1514	220	004	NaN
723013	KILM	1996	09	08	1733	110	006	NaN
723013	KILM	1996	09	08	1742	190	006	NaN
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723013	KILM	1996	09	08	1811	120	011	NaN
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723013	KILM	1996	09	08	1827	130	009	NaN
723013	KILM	1996	09	08	1832	130	006	NaN
723013	KILM	1996	09	08	1840	080	005	NaN
723013	KILM	1996	09	08	2000	330	015	022
723013	KILM	1996	09	08	2020	310	014	NaN
723013	KILM	1996	09	08	2100	300	012	NaN
723013	KILM	1996	09	08	2112	340	010	NaN
723013	KILM	1996	09	08	2118	310	007	NaN
723013	KILM	1996	09	08	2126	300	009	NaN
723013	KILM	1996	09	08	2135	300	008	NaN
723013	KILM	1996	09	08	2200	250	005	NaN
723013	KILM	1996	09	08	2238	180	006	NaN
723013	KILM	1996	09	08	2300	170	004	NaN
723013	KILM	1996	09	09	0000	180	003	NaN
723013	KILM	1996	09	09	0043	320	005	NaN
723013	KILM	1996	09	09	0100	NaN	000	NaN
723013	KILM	1996	09	09	0112	NaN	000	NaN

		Yr	Mo	Da	Hr	Dir	Sus	Gust
						(Knots)		
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723013	KILM	1996	09	09	0300	180	004	NaN
723013	KILM	1996	09	09	0400	NaN	000	NaN
723013	KILM	1996	09	09	0500	220	003	NaN
723013	KILM	1996	09	09	0600	220	003	NaN
723013	KILM	1996	09	09	0611	210	004	NaN
723013	KILM	1996	09	09	0634	NaN	000	NaN
723013	KILM	1996	09	09	0700	210	003	NaN
723013	KILM	1996	09	09	0800	220	005	NaN
723013	KILM	1996	09	09	0900	220	003	NaN
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723013	KILM	1996	09	09	1000	NaN	000	NaN
723013	KILM	1996	09	09	1100	230	004	NaN
723013	KILM	1996	09	09	1109	230	003	NaN
723013	KILM	1996	09	09	1200	240	004	NaN
723013	KILM	1996	09	09	1228	250	007	NaN
723013	KILM	1996	09	09	1242	240	006	NaN
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723013	KILM	1996	09	09	1307	240	007	NaN
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723013	KILM	1996	09	09	1336	250	007	NaN
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723013	KILM	1996	09	09	1412	260	008	NaN
723013	KILM	1996	09	09	1430	240	007	NaN
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723013	KILM	1996	09	09	1718	150	007	NaN
723013	KILM	1996	09	09	1727	140	006	NaN
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723013	KILM	1996	09	09	2100	210	006	NaN
723013	KILM	1996	09	09	2113	190	007	NaN
723013	KILM	1996	09	09	2200	200	007	NaN
723013	KILM	1996	09	09	2300	200	005	NaN
723013	KILM	1996	09	10	0000	190	006	NaN
723013	KILM	1996	09	10	0100	190	006	NaN
723013	KILM	1996	09	10	0200	190	006	NaN
723013	KILM	1996	09	10	0300	200	004	NaN
723013	KILM	1996	09	10	0400	200	003	NaN
723013	KILM	1996	09	10	0500	190	004	NaN
723013	KILM	1996	09	10	0600	NaN	000	NaN
723013	KILM	1996	09	10	0700	NaN	000	NaN
723013	KILM	1996	09	10	0800	NaN	000	NaN

		Yr	Mo	Da	Hr	Dir	Sus	Gust
						(Knots)		
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723013	KILM	1996	09	10	0833	NaN	000	NaN
723013	KILM	1996	09	10	0839	NaN	000	NaN
723013	KILM	1996	09	10	0843	NaN	000	NaN
723013	KILM	1996	09	10	0900	NaN	000	NaN
723013	KILM	1996	09	10	0903	NaN	000	NaN
723013	KILM	1996	09	10	0907	NaN	000	NaN
723013	KILM	1996	09	10	0916	NaN	000	NaN
723013	KILM	1996	09	10	0921	NaN	000	NaN
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723013	KILM	1996	09	10	0939	NaN	000	NaN
723013	KILM	1996	09	10	1000	NaN	000	NaN
723013	KILM	1996	09	10	1002	NaN	000	NaN
723013	KILM	1996	09	10	1010	NaN	000	NaN
723013	KILM	1996	09	10	1012	NaN	000	NaN
723013	KILM	1996	09	10	1014	NaN	000	NaN
723013	KILM	1996	09	10	1023	NaN	000	NaN
723013	KILM	1996	09	10	1044	NaN	000	NaN
723013	KILM	1996	09	10	1046	NaN	000	NaN
723013	KILM	1996	09	10	1100	NaN	000	NaN
723013	KILM	1996	09	10	1110	NaN	000	NaN
723013	KILM	1996	09	10	1114	NaN	000	NaN
723013	KILM	1996	09	10	1200	NaN	000	NaN
723013	KILM	1996	09	10	1300	230	004	NaN
723013	KILM	1996	09	10	1400	250	005	NaN
723013	KILM	1996	09	10	1500	170	006	NaN
723013	KILM	1996	09	10	1600	180	009	NaN
723013	KILM	1996	09	10	1614	160	011	NaN
723013	KILM	1996	09	10	1700	160	006	NaN
723013	KILM	1996	09	10	1725	170	004	NaN
723013	KILM	1996	09	10	1800	160	003	NaN
723013	KILM	1996	09	10	1804	190	006	NaN
723013	KILM	1996	09	10	1814	180	005	NaN
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723013	KILM	1996	09	10	1903	200	006	NaN
723013	KILM	1996	09	10	1931	170	010	NaN
723013	KILM	1996	09	10	2000	160	004	NaN
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723013	KILM	1996	09	10	2100	180	007	NaN
723013	KILM	1996	09	10	2116	180	011	NaN
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723013	KILM	1996	09	10	2200	170	006	NaN
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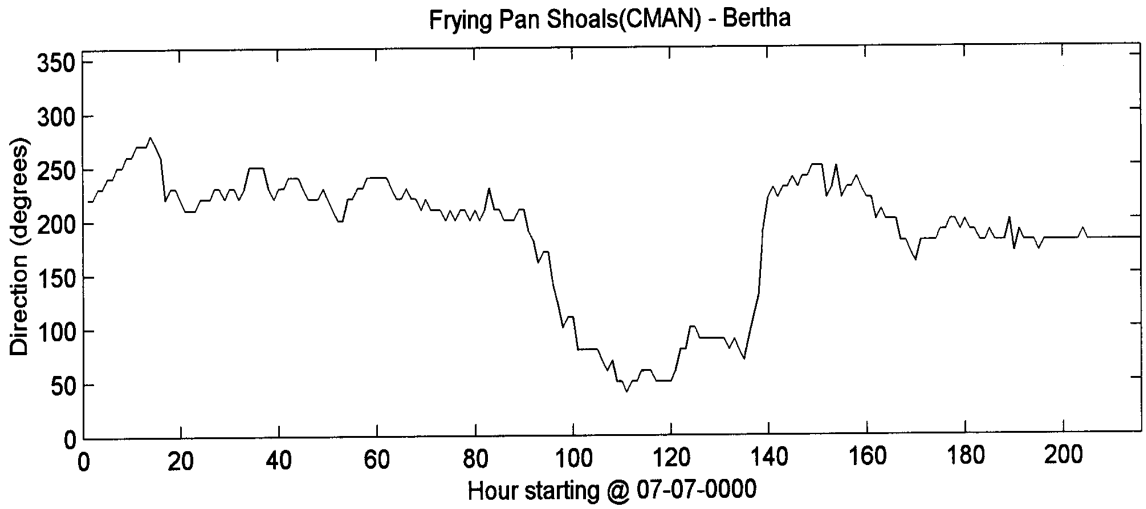
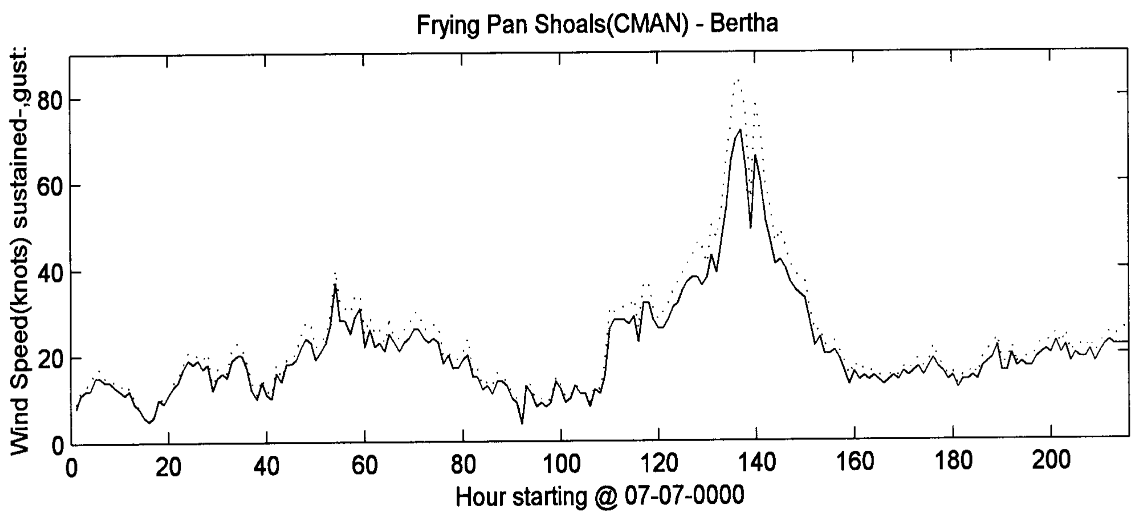
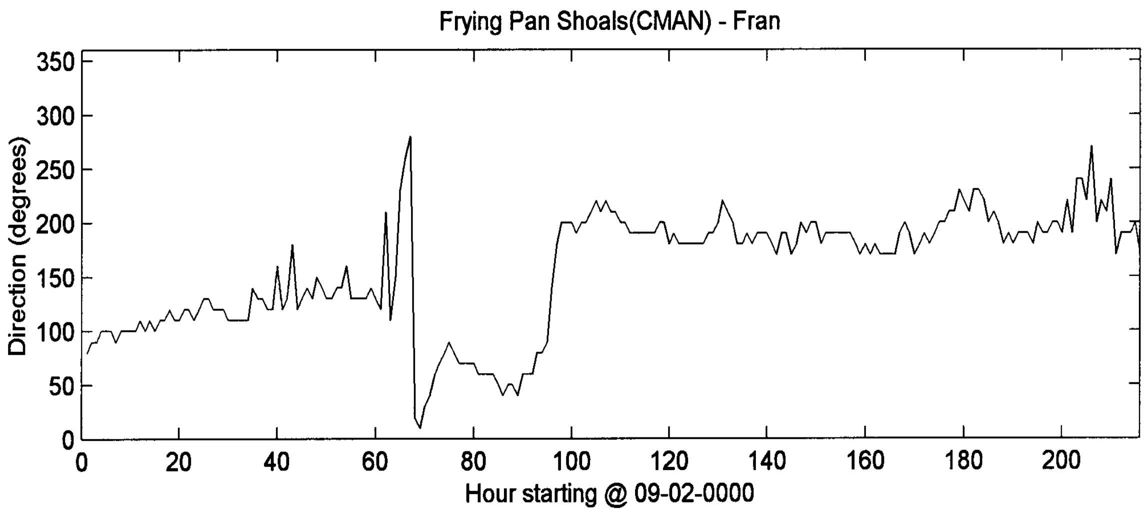
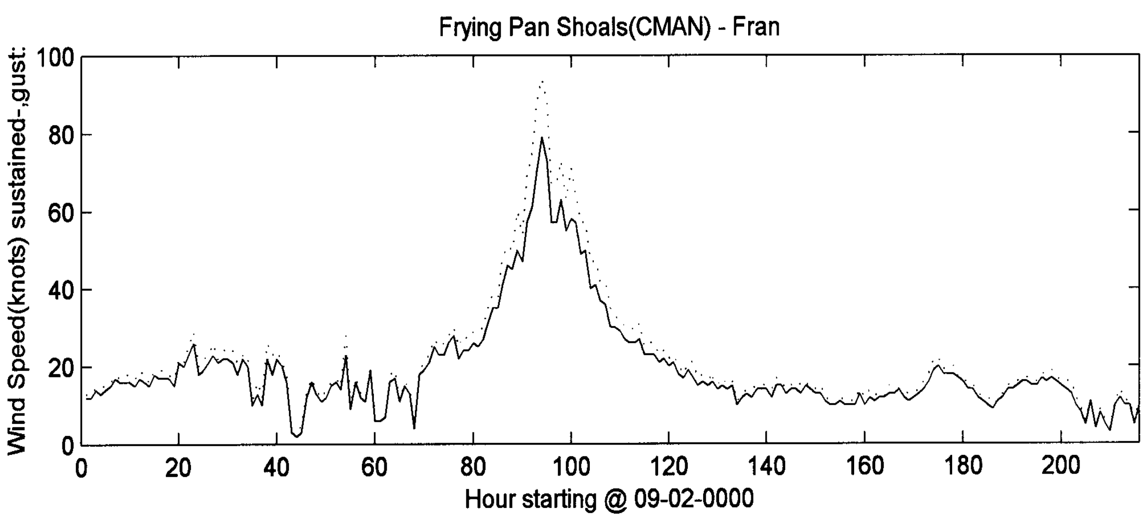
Plots of Wind Speed and Direction at Offshore Towers (Frying Pan Shoals and Cape Lookout)



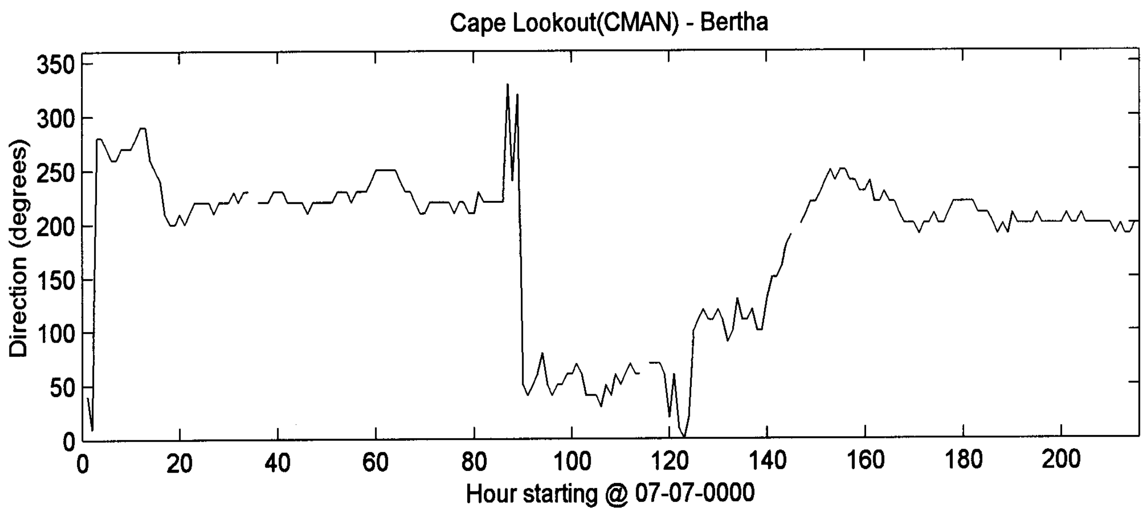


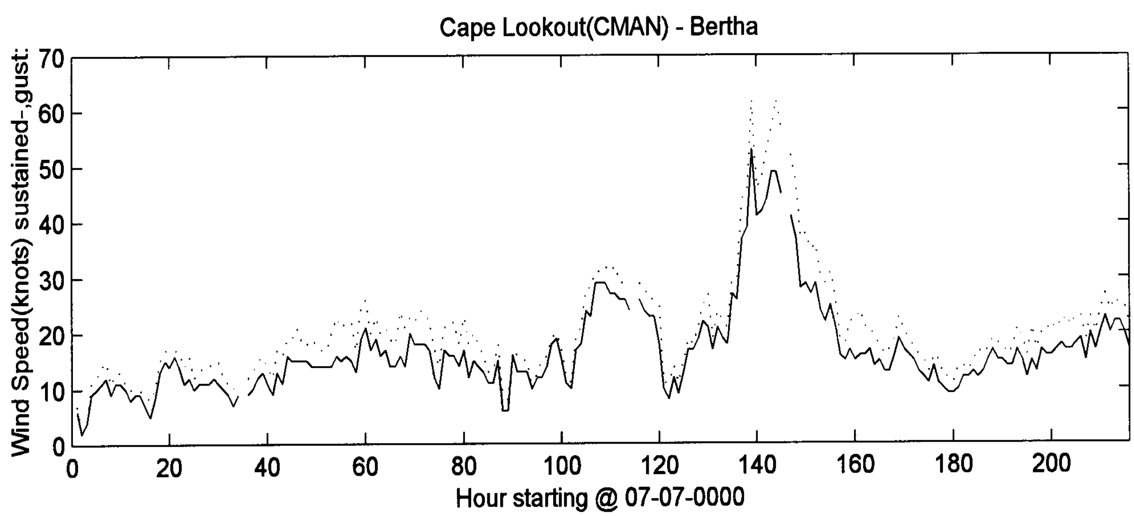


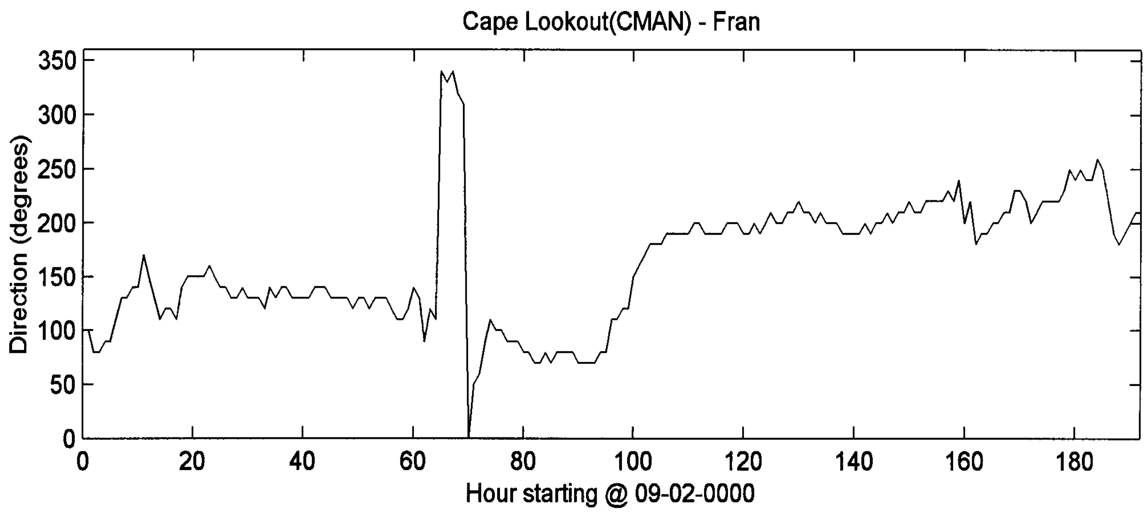
Frying Pan Shoals(CMAN) - Fran
Direction (degrees)
0
50
100
150
200
250
300
350
0
20
40
60
80
100
120
140
160
180
200
Hour starting @ 09-02-0000

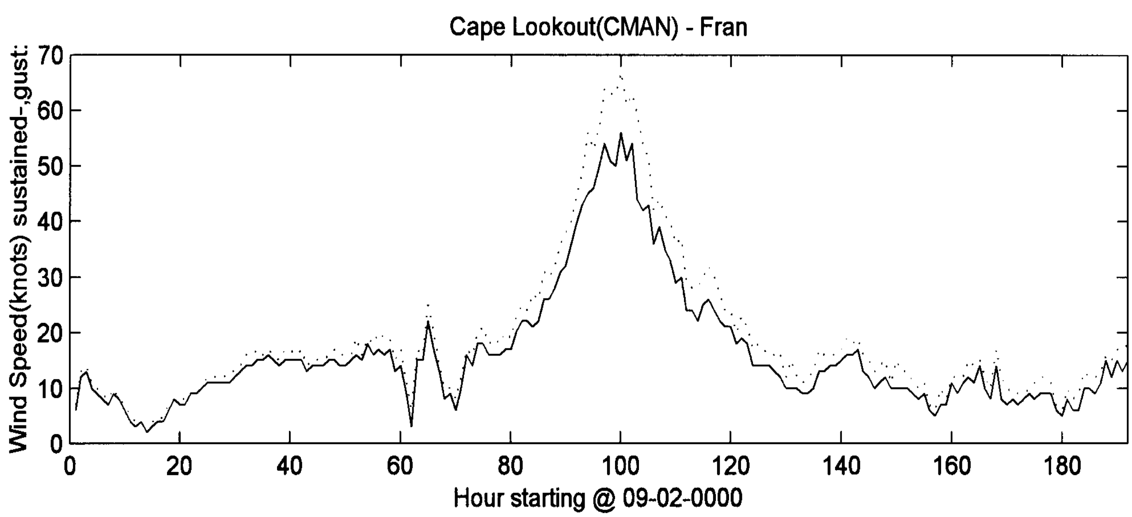


Frying Pan Shoals(CMAN) - Fran
Wind Speed(knots) sustained-,gust:
0
20
40
60
80
100
0
20
40
60
80
100
120
140
160
180
200
Hour starting @ 09-02-0000

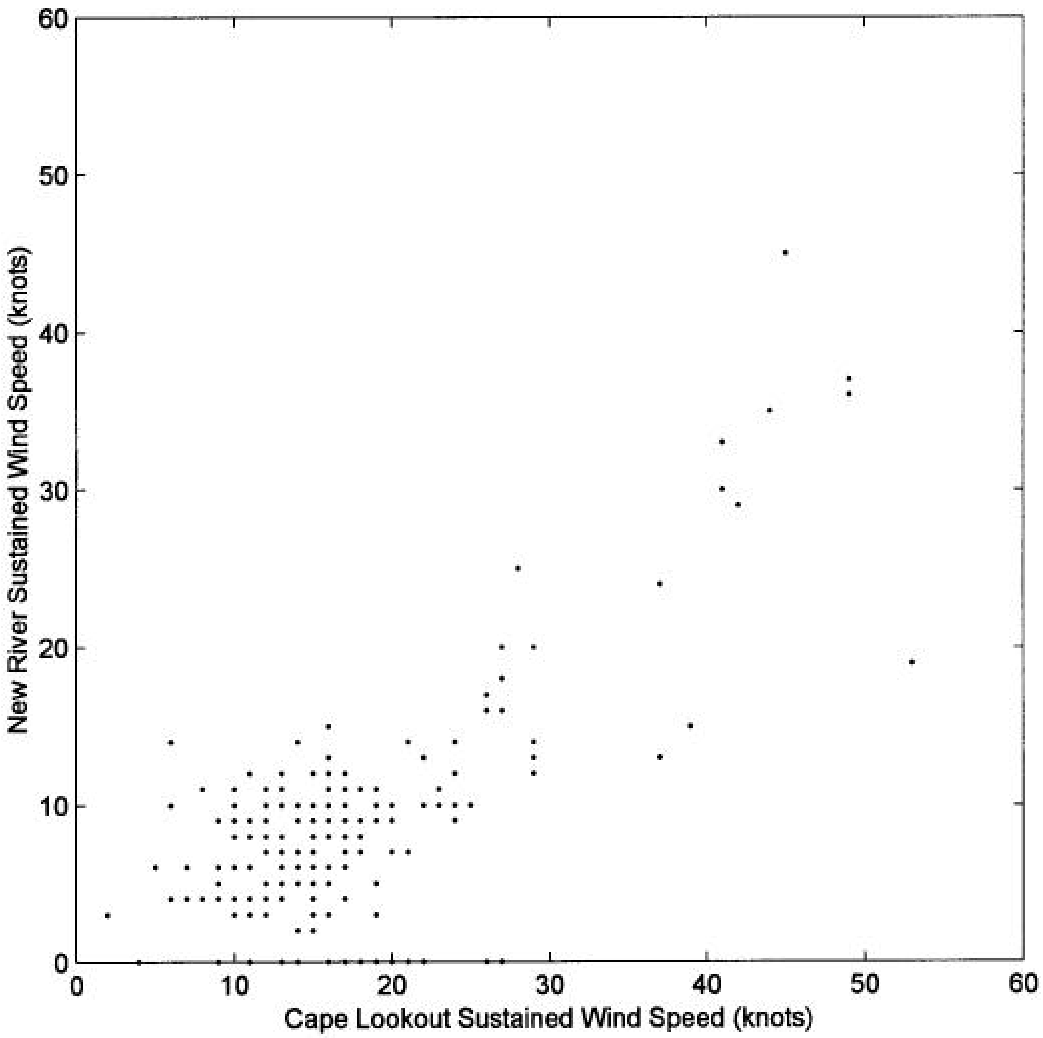

Cape Lookout(CMAN) - Bertha
Direction (degrees)
350
300
250
200
150
100
50
0
0
20
40
60
80
100
120
140
160
180
200
Hour starting @ 07-07-0000


Cape Lookout(CMAN) - Bertha
Wind Speed(knots) sustained-,gust:
70
60
50
40
30
20
10
0
0
20
40
60
80
100
120
140
160
180
200
Hour starting @ 07-07-0000

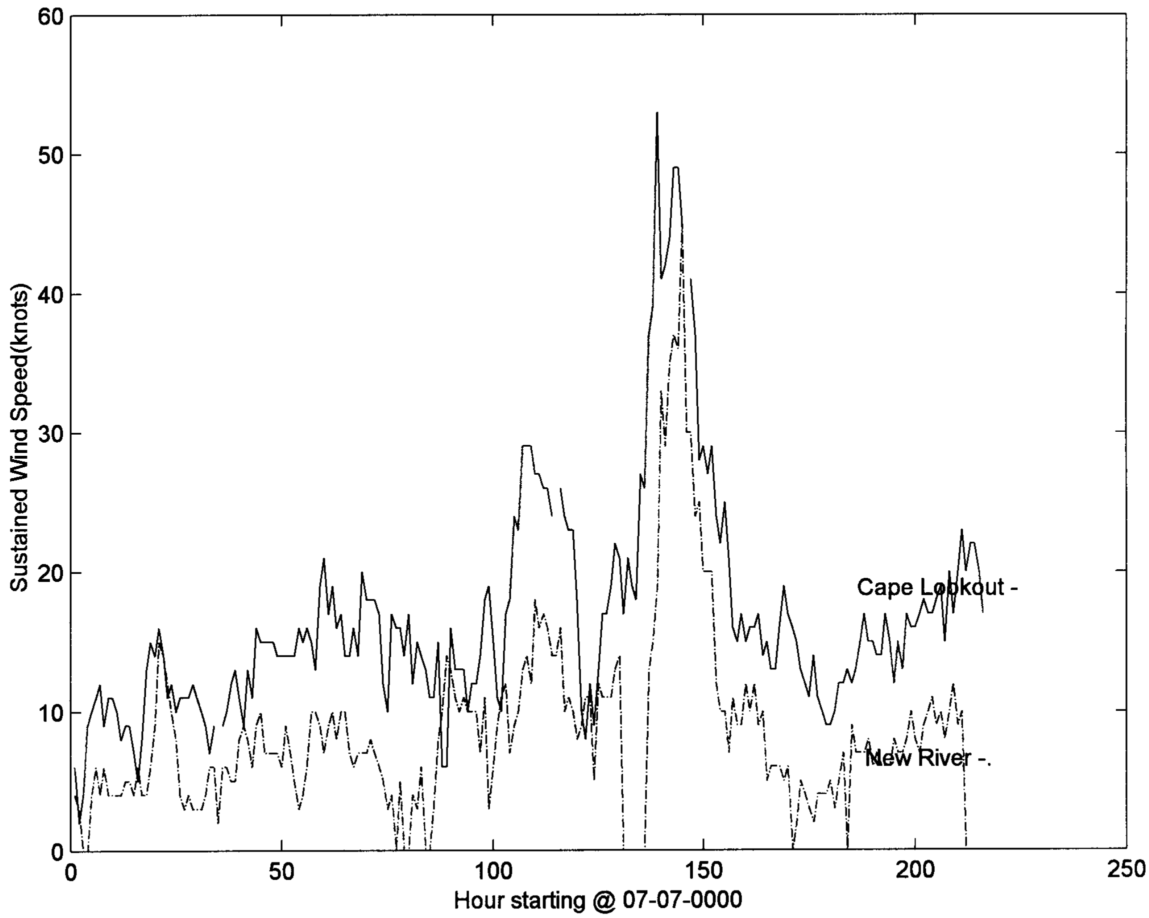

Cape Lookout(CMAN) - Fran
Direction (degrees)
0
50
100
150
200
250
300
350
0 20 40 60 80 100 120 140 160 180
Hour starting @ 09-02-0000

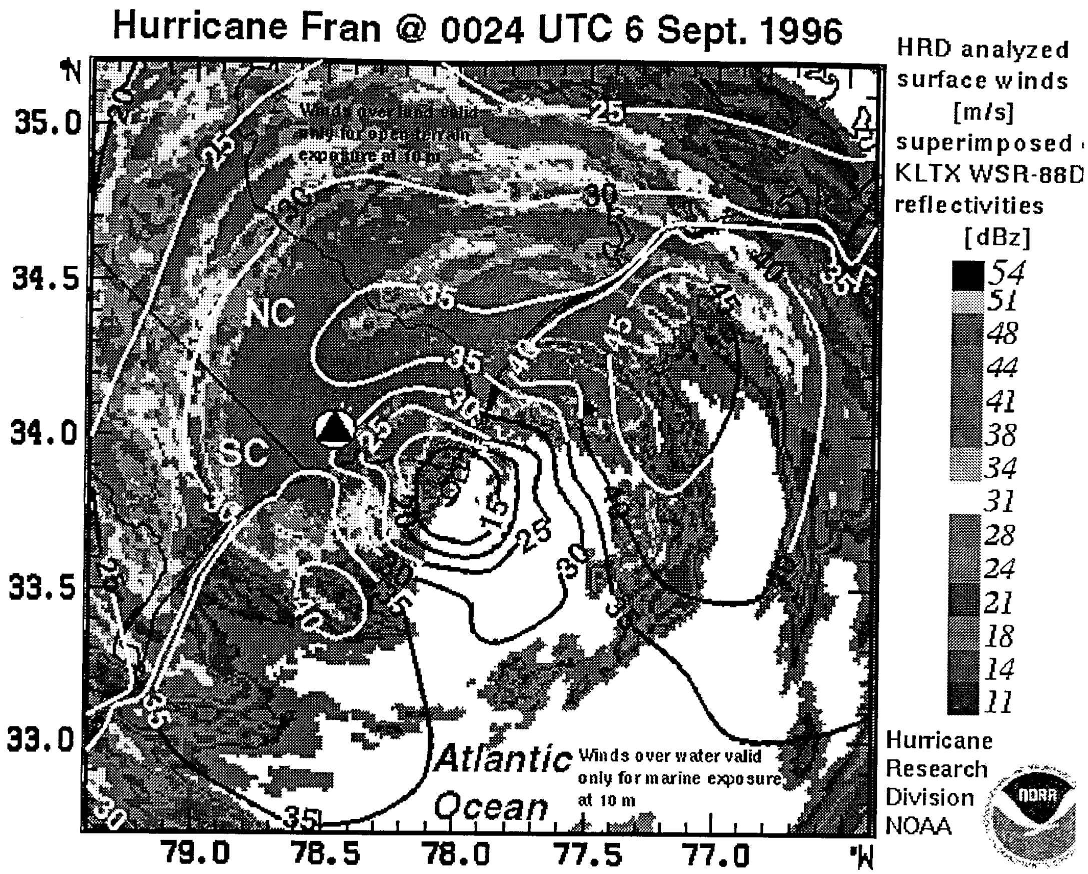

Cape Lookout(CMAN) - Fran
Wind Speed(knots) sustained-,gust:
0
10
20
30
40
50
60
70
0 20 40 60 80 100 120 140 160 180
Hour starting @ 09-02-0000

Scatter Plot of Sustained Winds at two Locations to Serve as a Check



Plotted Sustained Winds at two Locations to Serve as a Check




Hurricane Fran @ 0024 UTC 6 Sept. 1996
HRD analyzed surface winds [m/s] superimposed
KLTX WSR-88D reflectivities [dBz]
54
51
48
44
41
38
34
31
28
24
21
18
14
11
NC
SC
Atlantic Ocean
Winds over water valid only for marine exposure at 10 m
°N
35.0
34.5
34.0
33.5
33.0
79.0
78.5
78.0
77.5
77.0
°W
Hurricane Research Division NOAA

APPENDIX D
WAVES

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Wave Modeling Procedures.

<u>Equation (1)</u>. The wave modeling effort was performed in two stages, using two modeling technologies, WAM (Komen et al 1994) for the basin, region, and sub-region scales of the project. For the nearshore domain STWAVE (Smith et al 1999) was used and coupled to the surge estimates generated by ADCIRC (Chapter 3 Paragraph B). Both modeling technologies solve the action balance equation:

$$\frac{\partial}{\partial t} N + (\cos j)^{-1} \frac{\partial}{\partial j} (j \cos j N) + \frac{\partial}{\partial l} (\dot{l} N) + \frac{\partial}{\partial w} (\dot{w} N) + \frac{\partial}{\partial q} (\dot{q} N) = S \quad (1)$$

where N = action density (function of frequency f, direction θ, space, and time t)
action density is defined as energy / intrinsic angular frequency
ϕ = is the y coordinate
λ = is the x coordinate
θ = is the direction
ω = is the radial frequency
S = are the source/sink terms ($S_{in} + S_{nl} + S_{ds} + S_{w\text{-}b}$)

<u>WAve Model</u>. WAM is a third-generation model, where no a priori assumptions governing the spectral shape are applied as in the case of second-generation models. In addition, the specification of the source/sink terms: the atmospheric input (S_{in}), the nonlinear wave-wave interaction (S_{nl}), high frequency dissipation, or white-capping (S_{ds}), and for arbitrary depth application wave-bottom effects ($S_{w\text{-}b}$) are solved explicitly in the same frequency/direction space of the modeled spectrum. The action balance equation is solved for the spatial and temporal change in the directional wave spectrum. It is solved first for the propagation effects, or terms 2-4 on the left-hand side of Equation 1. The source/sink terms are then solved over the entire domain.

<u>STeady WAVE</u>. STWAVE solves the spatial rate of change in energy density (N=E/Τ where E is energy density) described by a 2-D spectrum. STWAVE neglects the time rate of change or the first term on the left in Equation 1, however, it can accurately simulate temporal changes in the nearshore wave environment. This can be accomplished without loss in accuracy provided that the STWAVE domain is sufficiently close to the coast and that all energy described by the offshore boundary has sufficient time to propagate through the entire domain to the shore. A *pseudo-time stepping* procedure is performed, by forcing the STWAVE domain with spectra at a fixed boundary at hourly time steps.

Wave Model Verification.

Hurricane Bertha Regional WAM Comparisons.

Figures C-1 and –2 display time plots of comparisons between WAM and measurements for the energy based wave height (or, H_{mo} derived from the integration of the 2-D spectrum in frequency and direction) for Bertha at Buoy 41002 and at Frying Pan Shoals. It was unfortunate that data were not available from buoy 41002, because WAM show two distinctive peaks in the wave height trace. At the Frying Pan Shoals, only one peak in both measurements and model results occurred. In general there is a fairly well defined wave height gradient evident in the maxima derived from either the model or measurement results. This gradient ranges from a minimum of about 5.8m (at 41002) to a maximum of 8.8m at Frying Pan Shoals. One must also note the water depth in the area surrounding Frying Pan Shoals is approximately 14m, and depth induced wave breaking occurred.

Figure C-1: Wave Height Comparison for Bertha Buoy 41002

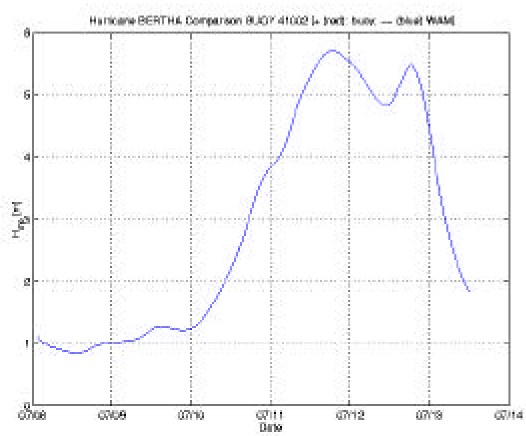
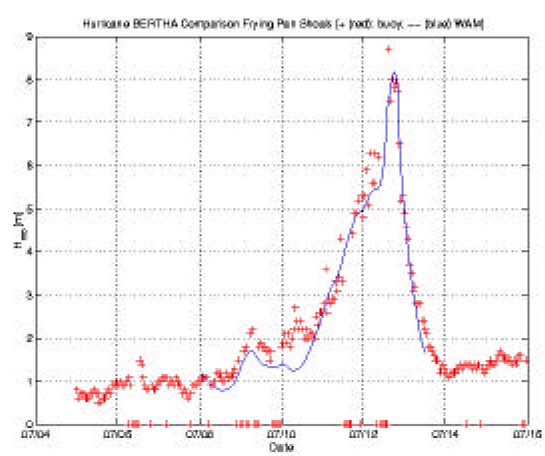


Figure C-2: Wave Height Comparison for Hurricane Bertha Frying Pan Shoals.



Hurricane Fran Regional WAM Comparisons.

As indicated in **Figures C-3 and C-4**, WAM compares exceptionally well to the buoy site with exception of under estimating the peak of Edouard because of the winds. For the Fran time period, the growth sequence, storm peak, decay, and the phasing at the peak of the storm are well replicated. Peak to peak comparisons under estimate the maxima at Buoy 41004 by 0.25m. Frying Pan Shoals shows nearly a 1:1 correspondence of 9.6m. These comparisons demonstrate again the wind field's accuracy, and also the reliability of WAM estimating hurricane wave conditions. It also provides a basis of credibility for the remainder of the wave model simulations and into the nearshore domain.

Figure C-3: Wave Height Comparison for Hurricane Fran Buoy 41002

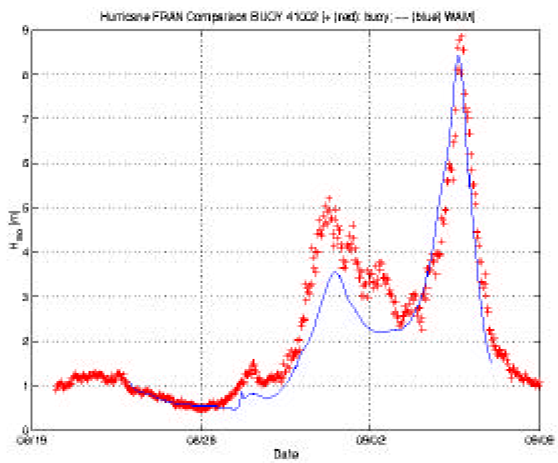
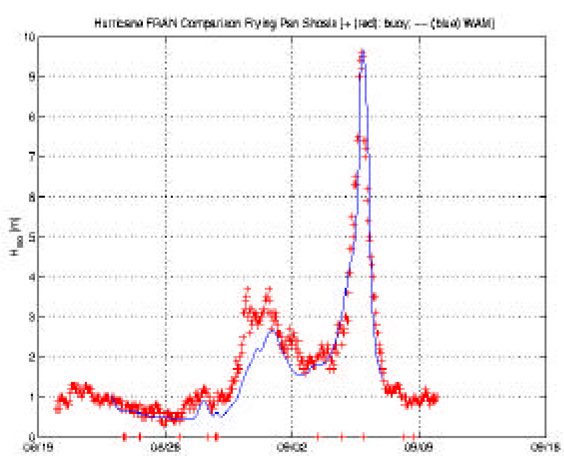


Figure C-4: Wave Height Comparison for Hurricane Fran Frying Pan Shoals



Coupled Wave (STWAVE) and Surge Estimates.

Simulation of the combined effect of water level variations on a wave model for the 4 specified study sites are dependent upon the water level estimates derived from ADCIRC, the elevation/water depth information and the wave modeling technology in the estimation of the local scale wave climate. Unlike the region and sub-region domains, inaccuracies in the elevation data of ±1 m will have a significant impact on whether land is flooded by the surge, because the maximum storm surge levels ranged from 1.46 to 1.61 meters. As previously mentioned, the number of elevations were limited to the resolution of the ADCIRC finite element grid at the study sites. These estimates were then spatially interpolated (two-dimensional cubic spline fit) to the STWAVE model grid with a final resolution of approximately 200 meters.

The surge levels from ADCIRC were used as input conditions to STWAVE. At each time interval the STWAVE water depth grid (now described with bathymetry seaward of the shoreline and elevation information landward) was adjusted to include the surge. If landward points were susceptible to flooding, the STWAVE grid was modified and included those points as water. The offshore water depths were also adjusted.

STWAVE was run in a *pseudo-time stepping* mode. Forcing conditions were provided from input spectra generated from the WAM sub-region simulations, a wind condition (assumed to be spatially constant over the domain) and the water level estimates derived from ADCIRC. The latter information was used to adjust the STWAVE water depth grid at each time step of one hour. The 2-D spectra were transformed, energy added if the winds were blowing ±45° from perpendicular to the orientation of the STWAVE grid system. For the two hurricane simulations, the input spectra were nearly saturated with energy so only about 2-5 percent additional energy was added.

As in the case of the WAM sub-region simulation, the best form to present the final wave estimates are significant wave height color contour plots occurring at the peak of Bertha and Fran.

Final Report
for
Contract

DACW54-98-P-3225

HURRICANE IMPACTS AND BEACH RECOVERY IN SOUTHEASTERN NORTH CAROLINA: THE ROLE OF THE GEOLOGIC FRAMEWORK

by

William J. Cleary

22 April 1999

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Figures (see Geology: Figures)

<u>Plates (see Geology: Plates)</u>

A. INTRODUCTION

Data concerning the impact of Hurricanes Bertha and Fran in 1996 upon the NC coastline suggest that the underlying geologic framework played a varying influential role in determining the shoreline response and subsequent beach recovery along various shoreline segments. Each shoreline reach within the 115km long impact area between New River Inlet and Cape Fear NC, as well as different segments of the same shoreline reach, responded with varying degrees of susceptibility to damage and recovery. Some coastal segments (Wrightsville and Carolina/ Kure Beaches) have recovered through natural processes and profile manipulation; however, many severely impacted areas (much of Topsail Island) are now at an even higher risk due to the sand deficit produced by the recent storms. Millions of cubic meters of sand were transported either across the low profile barrier islands or onto the shoreface, a major portion of which is permanently lost to the beach system. This does not bode well for the future of those shoreline segments without renourishment plans and with a continued interest in shoreline development. Some coastal areas along Topsail Island are so damage prone that future development should be seriously re-evaluated.

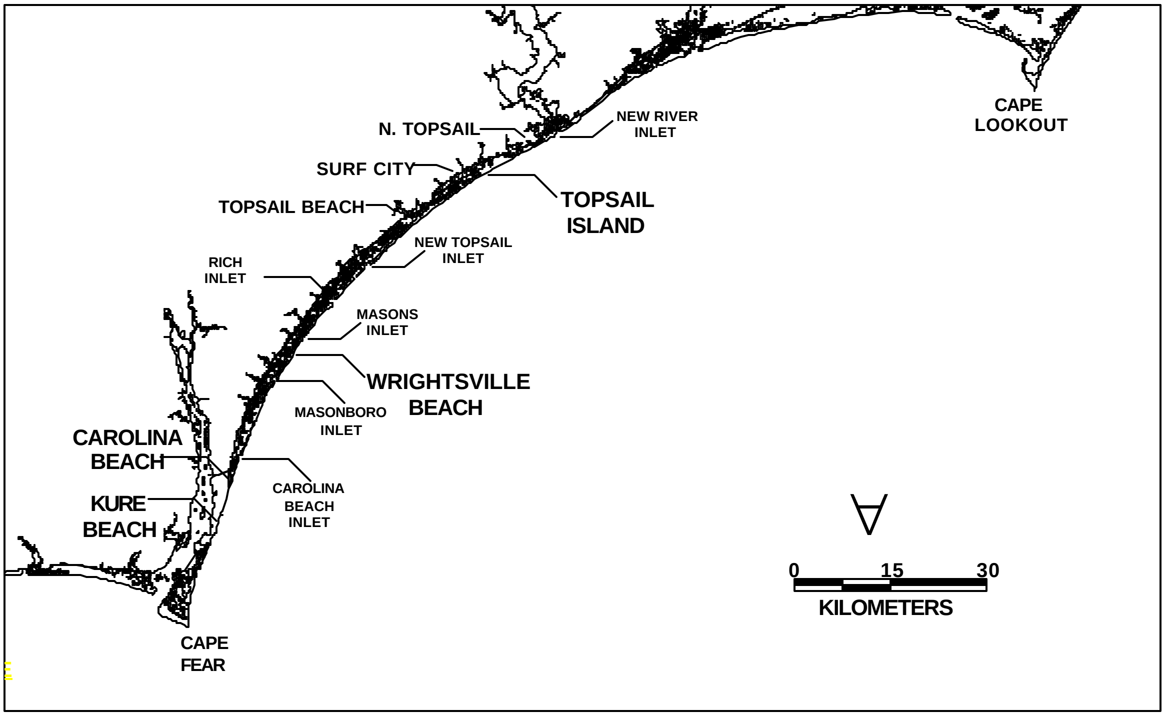
This report will consider the site-specific geologic settings of six study sites that include North Topsail Beach, Surf City and Topsail Beach along severely impacted Topsail Island, as well as Wrightsville, Carolina and Kure Beaches where impacts varied considerably. The study is approached from the perspective of how the underlying geologic framework (beneath the shorelines and shoreface) might have influenced the individual shoreline segments response to the hurricanes (**Figure E-1**).

B. METHODS AND APPROACH

To accomplish the objectives, critical databases (i.e., seismic, sidescan, vibracore, and surface sediment, etc.) were integrated from the shoreface with data from each of the shoreline reaches. The study sites consist of both headland and barrier segments for which there are a variety of onshore and offshore data. Various levels of quality, completeness, and interpretation characterize these data.

Sidescan sonar and high-resolution seismic surveys are available for the offshore portion of most of the study sites. Some of the sidescan sonar and seismic data exist in GIS coverages that have been used to define salient morphological features and the specific nature of the shoreface. Key elements that have aided the interpretation of the remotely sensed data are extensive diver seafloor observations, vibracores, and "field" maps describing the shoreface. From these data, mosaic maps of the seafloor, geologic facies maps, geologic cross sections, morphological maps of the shoreface and 3-D models for some of the study sites were generated.

Figure E-1: Location Map



C. GEOLOGIC SETTING OF THE IMPACT AREA

The coastwise configuration of the entire North Carolina coastline reflects major differences in the heritage derived from the underlying geological framework. Cape Lookout separates the North Carolina coastal system into two large-scale coastal provinces. Each province has a unique geologic framework that results in distinctive types of headlands, barriers and estuaries.

The four study sites are located within the southern province that extends from Cape Lookout to Sunset Beach, NC. Primarily relatively old rock units underlie the entire region. These rocks which range in age from the Upper Cretaceous through the Pliocene are associated with the Carolina Platform which underlies the region (**Figure E-2**). This structural platform has risen slightly causing the rocks to dip to the north and east, causing them to be truncated by the landward migrating shoreline and shoreface system (Riggs et al., 1995). Consequently, an erosional topography exists along the southern coastal province with exposures of these rock units on the shoreface. Scattered Pleistocene rock units occur in the far southern reaches of the study area particularly off the Carolina/Kure Beach headland segment.

The storm impact area can be further subdivided into a series of shoreline reaches based upon different spatial orientation of the shoreline, shoreface gradient and salient bathymetric features such as shore-attached ridges and hardbottom features. These variables determine the nature of the storm and hydrodynamic settings that define the specific shoreline physiography, storm response and beach recovery.

The southwest portion of Onslow Bay is a broad, shallow, high-energy shelf system (FigureE-1). Unconsolidated sediment cover is thin and variable as indicated by a large frequency of rock outcrops. Holocene sediment accumulation in Onslow Bay is negligible due to 1) low fluvial input, 2) entrapment of sediments in extensive estuarine systems, and 3) lack of sediment exchange between neighboring Raleigh and Long Bays (Cleary and Pilkey, 1968; Milliman et al., 1972; Cleary and Thayer, 1973; Blackwelder et al., 1982; and Riggs et al., 1995). Holocene sediment distribution and composition is controlled largely by the outcrop pattern of Tertiary and Quaternary sequences. It consists of a mixture of residual or palimpsest sediments derived from the erosion and reworking of the underlying stratigraphic units (Luternauer and Pilkey, 1967; Cleary and Pilkey, 1968; Macintrye and Pilkey, 1969; Cleary and Thayer, 1973; Mixon and Pilkey, 1976; Crowson, 1980; Blackwelder et al., 1982; Riggs et al., 1985; Snyder et al., 1982; and Hine and Snyder, 1985). A series of eroding headlands occur along the North Carolina coast (Cleary and Hosier, 1979; 1987; Pilkey et al. 1993; and Riggs et al., 1995). These represent paleo-topographic highs of Pleistocene or older units that occur in the subsurface. The Carolina Beach/Kure Beach and North Topsail Beach areas are examples of headland influenced shorelines.

1. <u>TOPSAIL ISLAND BACKGROUND AND SETTING</u>

Topsail Island is the second longest barrier within the Onslow Bay section of North Carolina. The island is bordered by the New River Inlet to the north and New Topsail Inlet to the south (Figure E1). The island is approximately 38 km long and averages approximately 280 m in width. The northeast-southwest barrier orientation exposes the island to frequent winter storms. Prior to 1941, the island then known as Ashe Island, was used as a stock grazing range, with no development or access to the mainland. Between 1941 and 1947 the island was used as a US Military Reservation. The military constructed the first paved road and provided a drawbridge for access to the mainland. Development began in the early 1950's several years after the island's ownership returned to the private sector. The island consists of three communities: North Topsail Beach, which comprises the northern 18.7km section, Surf City, which covers the central 8.8km of the barrier and, Topsail Beach, which extends along the southern 7.2km of the island. All three were severely impacted by the Hurricanes of 1996.

Topsail Island is situated in a severe or chronic overwash zone (**Plate E-1**). Storms during the period 1944 to 1962, and the late 1980's were particularly devastating to the island. In 1989 Hurricane Hugo impacted several sections of the island particularly North Topsail Beach. Hurricane Hazel (1954) and the Ash Wednesday storm (1962) caused significant damage along the entire barrier. Hurricane Hazel generated a 2.9m above mean sea level (MSL) flood level on an island whose average elevation is 2.7m above MSL. Sand was transported across the island toward the sound and marsh in the form of washover fans. The grasslands and dune fields rest upon washover fan and terrace sediments. The crenulate border of the shrubs marks the landward edge of the overwash fans/terraces. During Hurricane Fran much of the island was overtopped resulting in the formation of massive and extensive washover topography. Washover penetration along North Topsail beach ranged from 20m to 300m (**Plates E-2 and E-3**).

The dune system along most of the island prior to Hurricane Fran was generally a single foredune often scarped. Along major portions of northern and southern extremities of the island an artificial dune fronted much of the North Topsail and Topsail Beach communities. Some areas had multiple dunes, such as the 1km segment downdrift of New River Inlet.

Three inlets have affected the morphology and erosion patterns along Topsail Island since 1800. These inlets are New River, Stumpy and New Topsail Inlets. Stumpy Inlet opened and closed in the mid-1800's. The extensive vegetated flood tidal delta of this inlet is now the site of Surf City. This low area was one of the hardest hit areas along the entire island.

a. North Topsail Beach.

New River Inlet forms the northern boundary of Topsail Island, and fronts the largest coastal plain estuary in the Onslow Bay compartment (Figure E-1). The position of the inlet is controlled by the location of the ancestral channel of the river system. Cores, seismic data and the distribution of outcrops on the shoreface indicate the paleochannel is incised into the Belgrade Formation (**Figures E-3 and E-4**). As a result of this incision, the shallow inlet has migrated within a 3km wide zone. The current position of the inlet marks the southern boundary of this zone.

The hydrodynamics of this inlet and estuary were changed considerably by the dredging of the Atlantic Intracoastal Waterway (AIWW) and the channels connecting the estuary with the open ocean. The earliest photographs (1938) and charts indicate the inlet and the main channels were clogged due to reduced tidal flow. In 1940 a 3.7km long navigation channel was dredged connecting the Waterway with the inlet. The early 1960’s marked the advent of sidecast dredging of the throat and outer bar channel for navigation purposes.

The morphology and erosion/accretion patterns of the inlet’s shoulders have changed appreciably since 1960. During the past 38 years the portions of the Topsail Island oceanfront adjacent to the inlet has prograded more than 40 m. In contrast chronic erosion has characterized the Onslow Beach shoulder. The erosion and accretion trends are related to the slow southwesterly migration of the inlet and the location of the ebb channel on the Topsail Island shoulder. The asymmetric development of the ebb delta favored the welding of swash bar packages along the Topsail Island shoreline. Accretion associated with the inlet extends along a 1.5km zone and represents the only segment along the northern end of the barrier experiencing progradation (Plate 1). All of the multi-unit dwellings along the northern end of the island are sited seaward of the 1960 shoreline. The multiple dunes protected most of these structures from the structural damage that characterized the beach further south (Cleary, 1996; and Cleary and Pilkey 1996).

b. <u>North Topsail Beach Shoreface Characteristics</u>.

From the beach toe seaward, the shoreface off North Topsail Beach is predominately composed of outcrops with a thin, patchy veneer of carbonate-rich palimpset and modern quartzose sediments (Johnston, 1998). Thicker sediment accumulations occur in topographic lows, typically associated with scarps or depressions and channel features (**Figure E-5**). The northern portion of the study site is dominated by a platform-like feature composed of well indurated, Oligocene sandy moldic limestones (**Figures E-6 and E-7**). The irregular nature of this limestone platform probably influences the incident waves and the erosion along the local headland influenced beaches. Salient bathymetric features are located on both sides of New River Inlet. Fathometer sonargraphs (**Figure E-8**) from this region generally show a highly irregular karstic surface with low (<0.5 m) and high relief (>2.0 m) scarped hardbottoms bordering flat hardbottoms. The frequency of hardbottoms and scarps increases from the southern end of North Topsail Beach to the north, and spacing between the scarps generally varies considerably. Relief of the scarped hardbottoms increases north of Alligator Bay (Figures E-3 and E-4). Moderately high-relief (1-1.5m) landward facing scarps are common in this area. Presumably these features and the intervening plateau-like hardbottom areas exerted a major influence on sediment transport during and after the passage of Hurricane Fran.

The bathymetry seaward of the central portion of North Topsail Beach shows several poorly defined shore-normal linear topographic lows. These linear features appear to be channels or channel-like topographic lows that trend to the south and southeast and are bordered by variable relief hardbottoms (Figures E4, E5 and E6). Although one meter high scarps occur along the southern portion of the area, the sea floor relief is generally more subdued (Figure E-8). This difference in bathymetry probably reflects a different underlying rock type. Sonargraphs from the southern end of the study area generally show smoother profiles. A small number of diver observations are available for the southernmost profiles. The information indicates the bottom is composed of sand that has buried the underlying low relief hardbottom units.

(1). <u>Seismic Data</u>.

Interpretation of the seismic data is based on a summary of unpublished data (Johnston 1998). The seismic data were related to rock units based on correlation between the units exposed on the Topsail Island shoreface and those exposed at inland quarry locations in Onslow County. The uppermost stratigraphic unit recorded in the seismic data outcrops over most of the shoreface, and is correlative to the upper Oligocene Belgrade Formation. Another unit outcrops off Topsail Island seaward of the Alligator Bay area and is correlative to the lower Oligocene Trent Formation (Figure E-6).

Well-indurated sandy limestones of the Belgrade and Trent Formations are exposed over most of the northern portion of the North Topsail Beach shoreface, and are truncated by the erosional surface of the seafloor (Figure E-7). Because these units crop out over most of the study area, their geometry and composition significantly affect the shoreface morphology and bathymetry. Channels of various ages and origins are incised into the limestones. Some of the rock infilled channels are represented as bathymetric highs. Other channels are backfilled with unconsolidated Quaternary fluvial sands and estuarine muds, and situated in bathymetric lows (Figure E-7).

(2). Sidescan Data.

A seafloor sidescan mosaic of the shoreface is limited to the region north of Alligator Bay to New River Inlet (Figures E-4 and E-5). Lighter colored areas on the mosaic correspond to finer sands, while darker colored areas correspond to coarser material and rock outcrops (hardbottoms). The inferred seafloor types were verified by diver observations. Sea floor observations and the sidescan sonar mosaic indicate that the shoreface along the northern portion of Topsail Beach is dominated by low to moderate relief (0.1-2.0m) hardbottoms. This extensive hardbottom area is a corrugated surface marked by numerous small-scale depressions. Generally, significant modern sediment accumulation is restricted to large-scale shore normal linear features that extend across the shoreface. These channel-like features are depicted in Figure 5 and represent sediment ponds formed by the local hardbottom relief.

The sediments contained within the seaward extensions of these features are usually less than one meter thick. These linear sediment accumulations are not imaged well on seismic profiles. Cores recovered along the length of North Topsail Beach indicate the surface of the underlying Oligocene limestone is undulating. The shape of the karstic surface is probably a result of the combined effects of dissolution, collapse and fluvial erosion during low stands of sea level. The section of the barrier that fronts Alligator Bay overlies a relatively deep saddle in the surface of the limestone. In this region the relief on the limestone is estimated to be 3.0 to 5.0m. The southernmost channel on the shoreface (Figure E-5) may be a seaward extension of the feature that forms Alligator Bay.

The aforementioned linear features, which comprise about 30% of the sidescan sonar mosaic, are filled with thin units of carbonate-rich gravelly sand. They are probably pathways for cross-shore transport of material mobilized during storm events (Figure E-5). The basal portions of the steep landward scarps of the adjacent intervening high hardbottoms are often fronted by coarse gravel or are scoured and free of sediment accumulation (**Figures E-9 and E-10**). These associations suggest that the scarps divert seaward directed sediment flows alongshore and into the intervening lows (Figure E-5).

The remaining portion of the shoreface is characterized by low to moderate relief hardbottoms and limited areas of high relief hardbottoms. Modern sediments usually form an exceptionally thin mobile veneer over the limestone hardbottoms. Generally the sediments contain up to 30 % gravel. Limestone clasts are common constituents reflecting the contribution of the underlying hardbottoms.

(3). General Stratigraphy.

The top of the Oligocene is an erosional unconformity with a very irregular surface that reflects the pre-Pleistocene system of drainages and intra-stream divides. Lowstands of sea level during subsequent glacial episodes, led to the erosion of much of this previously deposited sediment sequence, preserving only scattered remnants on the shoreface. A major sequence of

Pleistocene sediments underlies the present barrier/lagoon system and the mainland. The preserved sediments consist primarily of estuarine muds and peats.

The ongoing rise of Holocene sea level has produced the modern coastal system that is superimposed upon the Oligocene units and preserved remnants of the Pleistocene coastal sediments. The modern coastal system is riding up and over these older units, which are being eroded on the seaward side (Plates E-2 and E-3). Consequently, in coastal segments poor in sand (i.e., dominated by the Belgrade Formation or Pleistocene muds and peat) there is a deficiency of sand on the beach and across the shoreface.

(4). Shoreface Sediments.

The modern sediment cover on the shoreface off North Topsail Beach is generally too thin to vibracore, except in bathymetric lows or in the paleochannel of the ancestral New River. Four short vibracores (20-100 cm) taken within the hardbottom area immediately south of the inlet (Figure E3) contained graded shelly quartz sand and a very coarse basal unit with abundant rock fragments. Cores collected from the channel-like bathymetric lows were also very short (20 –30 cm) and consisted of gravelly sands overlying gray mud.

(5). Storm-Related Shoreline Impacts.

Dunes along the oceanfront were damaged to some extent as a result of Hurricane Bertha. The small amount of recovery due to natural recovery and artificial profile manipulation did little to improve the beach conditions before Hurricane Fran struck seven weeks later. Recession of the high water line (HWL) along North Topsail Beach due to these two storms was significant. The average overwash penetration associated with Hurricane Fran varied along the beach from 8m near the prograded dune segment to more than 260 m at the northern end. Changes in the island width following Hurricane Fran varied and were a function of the local conditions, which dictated the amount of foreshore retreat and overwash penetration. The coastwise changes in barrier width varied from an 18m decrease along the inlet-influenced segment to an increase of 248m near the storm breach. (Cleary et al., 1999).

Post storm bi-monthly topographic surveys were conducted between 8/97 and 8/98 at six stations established along an 8km long shoreline segment. The highest elevations recorded along the northernmost monitoring stations were the result of manipulation by bulldozing and fill placement. Seasonal changes were evident as the berm height and the profile steepness varied. The net changes during the storm-punctuated period amounted to a net gain of less than one meter. Along the breached segment of the barrier dramatic fluctuations in the foreshore were due to repeated bulldozing of the profile. Over 40m of the artificial dune and beach were eroded during Hurricane Bonnie (8/98). Another dune was then constructed in the fall of 1998. Little natural recovery has occurred south of the access road. Since the initial survey in 8/97 the HWL has retreated a net distance of 10m along much of this section of the shoreline.

c. Surf City.

Surf City occupies the central 8.7km of Topsail Beach (Figure E-1). The majority of the barrier in this vicinity fronts the relict flood tidal deltas of Stumpy Inlet that opened and closed several times during the eighteenth and nineteenth centuries. The finger canals were dredged in the mid to late 1960's across the surface of the marsh that caps the coalesced flood tidal deltas (**Plate E-4**).

The average long-term erosion rates published for the southern portion of Surf City range from zero to 2 ft/y. In contrast the northern portion of this shoreline segment was characterized by accretion rates up to 3 ft/y (Benton et al., 1993). These erosion rate data do not adequately portray the pre-storm shoreline conditions, particularly the nature of the dune line during the summer of 1996. In many places the dunes were low, scattered and often scarped. The areas with some of the worst damage were shoreline segments characterized by long term accretion (**Plate**s E-4 and **E-5**). Overwash in the aforementioned segments extended across much of the low-lying barrier and into the canals. The southern portion of Surf City was less susceptible to overtopping and overwash penetration was greatly reduced due to the topographically higher foredune and adjacent dune field.

In comparison to the other study sites little detailed information exists on the nature of the shoreface off Surf City. Reconnaissance surveys indicate the shoreface off Surf City beyond the toe of the active beach, is characterized by a very thin, mobile veneer of fine quartz sand and carbonate gravel overlying flat limestone hardbottoms. Bathymetric profiles depicted by **Figures E-11 and E-12** indicate the lack of significant relief across the limestone surface. The moldic limestone that crops out over much of this area has been correlated to the Oligocene Trent Formation. Preliminary mapping by divers indicates the low relief, well- indurated, moldic limestone is riddled by boring organisms and encrusted by a variety of epifauna. These bottom communities are not as well developed as they are off North Topsail Beach. The mobile nature of the bottom presumably precludes extensive development of these bottom communities. The periodic exposure of extensive areas of hardbottom presumably plays a role that affects near bottom currents and wave orbitals and ultimately cross-shore transport of sediment during storms. Much of the modern sediment cover consists of thin, graded beds overlying bored and encrusted limestone hardbottoms. This sequence suggests the thin sediment veneer is remobilized frequently.

d. Topsail Beach.

New Topsail Inlet (Figure E1) separates Topsail Island to the northeast and Lea Island to the southwest. Historic coastal charts and maps indicate this inlet existed as early as 1738. Since 1738, New Topsail Inlet has steadily migrated to the southwest, a distance of approximately 9.5 km. During the period 1856-1963 the inlet migrated 1830 m to the southwest at an average rate of 19.2 m/yr. Migration rates of 35 m/yr have characterized the inlet over the past two decades.

Inspection of controlled aerial photographs from 1938-98 suggests the inlet gorge has been positioned close to the Lea Island shoulder during the majority of the period. The orientation-of the main ebb channel across the ebb tidal delta platform has changed on a cyclical basis and as a result has dictated the patterns of erosion/accretion on the adjacent shorelines (Cleary, 1994).

Extensive beachfront development on the southern end of Topsail Island began in the early 1950's. The cottages and motels which date from this period were constructed on the primary dune which paralleled the southwesterly extending recurved spit. As New Topsail Inlet migrated, the bulbous recurved portion of the dune ridges also reformed to the southwest in accordance with the position of the inlet. Migration resulted in a realignment and truncation of the updrift trailing shoreline (Cleary, 1994).

The chronic erosion that currently characterizes this area, stems predominantly from the recession of the primary recurved dune line as the inlet has migrated. Erosion of oceanfront lots associated with New Topsail Inlet migration and spit elongation has been accelerated by the occurrence of numerous storms. Some of the most extensive washover fans and terraces developed during Hurricane Fran on Topsail Island were mapped in this area of Topsail Beach (**Plate E-6**).

(1). <u>Shoreface Characteristics.</u>

The data from reconnaissance studies of the shoreface off Topsail Beach consists of sidescan surveys obtained prior to Hurricane Bertha (4-6 July 1996); a follow up survey (1 August 1996), and a second resurvey in the aftermath of Hurricane Fran. Several different sidescan sonar systems were utilized and differences are reflected in the quality of the data. Fifty km of subbottom profiles, several vibracores and grab samples were also obtained.

The Topsail Beach shoreface is similar to the other study sites and is characterized as a sediment starved region where bioerosion and reworking of Tertiary and Pleistocene units provide the primary sources of modern sediments. A thin patchy veneer of modern sediments covers the flat to low relief Oligocene limestone hardbottoms (**Figures. E-13 and E-14**) and several incised Quarternary fluvial channels (McQuarry, 1998). The channels appear as dark colored areas, interpreted to be coarse sediments, on the sidescan sonar profiles. The continuity of the channels vary but some can be traced across the shoreface. Grab samples indicate the channels are lined with shell lag and minor amounts of quartz sand. Large, bored Mercenaria shells are found within and around the channel margins. A thin discontinuous silty quartz unit, less than 1 m thick, blankets the intra-channel and hardbottom areas (Figure E-13). This sediment is lithologicallly similar to the underlying unconsolidated Oligocene unit (McQuarry, 1998).

Overall, there was relatively little change associated with the hurricanes of 1996. No notable structural changes occurred within the areas dominated by hardbottoms. Because the sidescan sonar surveys were obtained with three different systems, there was some difficulty with interpretation of the images as the backscatter intensities varied. It was possible to ascertain that the greatest change recorded was the movement of the medium to fine grained sediments. Prior to Hurricane Bertha, there was a thin blanket of these sediments on some of the hardbottoms. Subsequent to both Hurricanes Bertha and Fran, additional areas of hardbottoms were exposed. In addition, the channel features on the pre-hurricane surveys, imaged as high acoustic backscatter areas on the sidescan swaths, appeared slightly obscured on the post-storm surveys. It is likely that a thin layer of sediment was deposited within the low areas that was initially characterized by coarse material (McQuarry, 1998).

(2). Storm-Related Shoreline Impacts.

Hurricane Bertha resulted in the overtopping of the southernmost 1.8km of Topsail Beach and the formation of minor washover topography. Following Hurricane Fran, the most extensive overwash occurred along the southern 3.4 km of Topsail Beach. Overwash terraces extended 100 to 200m across the flattened profile. Almost all of the dunes were eroded. North of the southernmost 3.4km shoreline stretch, overwash was sporadic. Newly formed washover topography varied along this segment encompassing the northern portions of Topsail Beach to the southern limits of the Town of Surf City. Some stretches showed no evidence of overtopping while other segments were completely overtopped.

It is difficult to determine the influence of the geologic framework upon the storm impacts along this shoreline reach and shoreface due to the lack of sufficient data. The fact that this area was a chronic erosion and overwash zone makes the task more difficult. The pre-storm condition of the southernmost portion of the Topsail Beach foreshore probably played a greater role in dictating the storm's impact and subsequent shoreline recovery. Much of the erosion over the past several decades along this section of the barrier stems from planform readjustments associated with the migration of New Topsail Inlet. Much of the erosion and structural damage recorded is related to the pre-storm erosion history and not the underlying geology. The geologic framework probably plays a significant role in the long-term morphology of Topsail Beach which is related to shoreface sediment sources and availability.

Shoreline recovery along Topsail Beach will be influenced by the regional availability of sediment on the shoreface. Studies of the shoreface within Onslow Bay have shown that hardbottoms are a significant source of sediment through bioerosion. While sandy limestone hardbottoms do exist off Topsail Beach, they are flat and often covered with a thin sediment veneer. The composition and morphology of the hardbottoms suggests that these areas contribute little to the overlying sediment cover and ultimately the beach system. The unconsolidated Oligocene sequence that forms the upper stratigraphic unit over portions of the shoreface is thought to be a major source of the fine sand and silt that blankets major portions of the area. Muddy material that has been reworked from the scattered paleochannels may also be a contributor. The availability of "beach-quality" material on a regional basis is limited. The lack of sediment on the shoreface translates to a lack of sand for the shoreline.

2. WRIGHTSVILLE BEACH AND SHELL ISLAND.

Wrightsville Beach is a 7.3km long developed barrier island located east of Wilmington (**Plates E-7, E-8 and E-9**). Because of its proximity to Wilmington, it was one of the first barrier islands in North Carolina to be developed as a resort. Bathhouses and summer cottages built in the 1860's were serviced by a trolley line that was completed in 1889. A compilation of data from aerial photographs and historical charts shows that the entire island rests on inlet fill. Moore's Inlet, now closed, was the major inlet in the area during the past century. Erosion on Wrightsville Beach is not a new problem. From the earliest attempts at building along the oceanfront, erosion problems have existed. For example, between 1923 and 1939, more than two dozen concrete and timber groins were emplaced along the shoreline in an attempt to halt erosion. The first attempt at replenishing the sand lost to erosion occurred in 1939, when sand was pumped onto the beach (USACE, 1982).

Between 1944 and 1965, four major hurricanes (including Hurricane Hazel in 1954) and a number of winter nor'easters resulted in significant shorefront erosion. In 1965, the Wrightsville Beach Erosion Control and Hurricane Protection Project was constructed along 4515m of ocean shoreline which extended north from the Masonboro Inlet jetty to the town's northern limit. Additional sand was pumped on the shore to close Moore's Inlet, located 450m north of the town.

Between 1938 and 1965, Moore's Inlet (now closed) migrated along a 1.5 km section of Wrightsville Beach and adjacent Shell Island. Historic aerial photographs, maps, and charts show this inlet affected the shape of the adjacent barrier island beaches by producing a convex shoreline protuberance immediately adjacent to the inlet (Plate E-8). This bulge is common along inlet influenced shorelines where sand packets in the form of swash bars derived from the protective ebb tidal delta weld onto the adjacent beaches. The end result is a shoreline that curves seaward. Following the artificial closure of Moore's Inlet (1965), the building line and roads along the new northern corporate limits were extended and basically paralleled the pre-closure curved shoreline. Much of the erosion along the restored northern part of Wrightsville Beach stems from the relict convexity of the restored shoreline (Plates E-7 and E-8).

Evidence for rapid erosion along the newly annexed portion of Wrightsville Beach fronting Moore's Inlet was obvious by the late 1960's. This recession necessitated the placement of additional sand on the northern half of the beach. By the middle 1970's, homes and structures along the northern flanks of the bulge were fronted by bulkheads and walls of protective rip-rap. Additional restoration efforts in 1980 and 1981 placed fill along the northern 2450m of the project, temporarily reversing the shoreline retreat. On five separate occasions additional sand was placed on the beach in an attempt to mitigate the erosion and provide storm protection. The U.S. Army Corps of Engineers estimate that the convex shape of the shoreline accelerates the annual erosion (Jarrett, 1977; USACE, 1982). Overwash and structural damage associated with Hurricane Fran was concentrated in this area where the structures are positioned seaward of the natural building line (Plates 7, 8 and 9). Without question the pre-storm condition of the beach along this reach dictated the impact of the storm and the subsequent shoreline recovery.

a. Wrightsville Beach Shoreface Characteristics.

Dr. E. Robert Theiler of the U.S. Geological Survey, Woods Hole (USGS-WH) and others have collected extensive geologic and geophysical data off Wrightsville Beach over the last decade. Over 300km of 3.5kHz subbottom profiles and 100kHz analog and digital sidescan sonar data have been obtained during these studies. The geophysical data covers a broad area of the shoreface. A suite of vibracores, surface sediment samples and diver observations was obtained between 1991-1992. In March 1994, a geo-referenced, high-resolution digital sidescan sonar mosaic of the shoreface was produced. Another digital sidescan sonar survey was conducted in early August 1995, followed by the collection of additional vibracores and samples. A portion of the shoreface was resurveyed following Hurricane Fran in September 1996.

The sidescan sonar surveys indicate that the morphology of the Wrightsville Beach shoreface is dominated by shore-normal and shore-oblique rippled scour depressions (Cacchione et al., 1984). These 40-100m wide features develop just seaward of the surf zone at 3-4 m water depths, and extend to 10m water depths. The rippled scour depressions are defined by areas of high acoustic reflectivity on the sidescan sonar mosaic and are floored with very coarse shell hash and quartz gravel (**Figure E-15**). On the upper shoreface the depressions are scoured up to 1m below the surrounding seafloor that is covered by fine quartz sand (**Figure E-16**). The depressions terminate and the shore-normal morphologic trend becomes shore-oblique at the base of the shoreface, presumably due to a series of east to northeast trending, low relief relict ridges (Thieler 1997; Thieler et al, 1998).

The more numerous depressions along the southern part of the Wrightsville Beach shoreface may be the result of increased bedrock control, as evidenced by larger areas of hardbottoms on the shoreface. On the 1992 sidescan sonar mosaic, small areas (20-50 m^2) of outcropping rock appear to be exposed above the fine sand between some of the depressions. Onshore data indicate that Tertiary limestone units occur in the near subsurface in the same area where rippled scour depressions are abundant offshore (**Figure E-17**). In addition, the gross morphology of the shoreface and inner shelf did not change over a 21-month period between the 1992 and 1994 sidescan sonar surveys. Surficial sediment distribution in the 1994 and 1995 surveys is nearly identical to a sedimentary facies map presented by Thieler et al, (1995) based on analog sidescan sonar data and surface samples collected in June 1992. These observations suggest that the locations of some rippled scour depressions may be controlled by bedrock related antecedent topography.

Preliminary data from the post-Hurricane Fran sidescan sonar survey indicate there was little noticeable change to the overall configuration of the large-scale depressions. This suggests that these features are relatively permanent. The data also suggests that the sediment cover both within the depressions and across the intra-depression regions was remobilized. Thieler et al, (1998), hypothesized that the rippled scour depressions act as conduits for cross-shore sediment transport. Furthermore, the variations in the shoreface topography coupled, with the complex barrier planform related to the Masonboro Inlet Jetty and Moore's Inlet closure, may enhance downwelling currents and sediment transport.

(1). <u>Shoreface Sediment Characteristics</u>.

The shoreface sediment cover off Wrightsville Beach is a patchy veneer blanketing low-relief, Tertiary units (**Figure**s E-17 and **E-18**). The modern sediment, including the sediments from the replenished beach, averages about 30cm in thickness. The primary underlying units are a Plio-Pleistocene arenaceous limestone, an unconsolidated Oligocene silt, and Quaternary fluvial channels (Snyder, 1994; Thieler et al, 1995 and Thieler, 1997).

Petrographic analyses of surface sediment samples indicate several distinct, local sources. The sources include the underlying rock units and small channels, in addition to the modern beach. For example, there are a number of locations in the area where limestone outcrops are present (Figures E15 and E17). Bioerosion of the outcrops produces residual sediment ranging in size from gravels to lime mud. This residual fraction is mixed with outcrop-associated, relatively fresh invertebrate fragments.

The similar mineralogy of the ancient unit and immediately adjacent modern sediments indicates the Oligocene unit is contributing glauconite-rich silt and very fine sand to the shoreface. Lagoonal sequences deposited during the Holocene have infilled relict inlet and tidal creek channels incised into the Tertiary units. Three radiocarbon dates for *in situ* oysters from these channels provide an age assignment of 8-10 ky. These deposits, some of which are visible on the sidescan sonar mosaics, are eroded and reworked during storms, providing a minor source of material for the overlying sediment cover.

Some of the sediment from the earlier beach replenishment projects can be found on the shoreface (Pearson and Riggs, 1981; Cleary et. al 1991; Thieler et. al, 1995). The fill is identifiable on the basis of its gray color, black-stained shell material, and high oyster shell content.

3. <u>CAROLINA BEACH TO KURE BEACH</u>.

Carolina Beach Extension marks the end of the barrier island physiography (Figure E-18). Carolina Beach Inlet impounds considerable quantities of sand moved alongshore. As a result, an offset has formed south of the inlet where overwash is a common occurrence (**Plate E-10**). Dunes along this section have little time to redevelop between washover events. This portion of the spit extending off the headland at Carolina Beach was the site of extensive washover topography during Hurricanes Bertha and Fran. Major overwash also occurred along much of the shoreline segment along and adjacent to the rip-rap (**Plate**s E-10 **and E-11**). Overwash penetration along the remainder of the replenished shoreline to the south was minimal (Plates E-10 and E-11).

The marsh-filled estuary found north of Carolina Beach does not exist behind the Carolina/Kure Beach section of the shoreline (Figure E-18 and Plate E-10). Elevations directly landward of the foreshore are 6 to 8m. In this area, an extensive eroding subaerial headland intersects the coast (**Plate**s E-10 and **E-12**). This shoreline segment consists of a wave-cut platform incised into Oligocene through Pleistocene units of the headland with a thin beach perched on top (DuBar et al., 1974; Moorefield, 1978; Meisburger, 1979; Cleary and Hoiser, 1979; Snyder et al., 1994, Riggs et al., 1995; Cleary et al., 1996).

Erosion resistant, cross-bedded coquina limestone and interbedded sandstone forms a protuberance in the shoreline north of Fort Fisher (Plate E-10). A friable, humate and iron-cemented Pleistocene sandstone forms the surface that underlies the modern beach along much of the Carolina Beach to Kure Beach area (**Plate E1-3**). Large, in-place stump forests were exposed along much of this reach after major storms, including after Hurricane Fran. These extensive outcroppings of the relict stump forest testified to the thin nature of the modern, perched sand prism (Plate E-13). Although some structural damage and overtopping occurred along the topographically higher backshore areas of Kure Beach, the higher elevations of the area immediately landward of the oceanfront were instrumental in preventing major damage (Plate E-13).

The underlying coquina and its associated lithologies form a widespread hardbottom mosaic that extends across much of this area (Cleary et al., 1996; Marcy and Cleary, 1997 and Marcy, 1997). The extensive series of low relief coquina outcrops on the shoreface may act as barriers that could significantly affect the refraction of wave energy, as well as the movement of sand across this shoreface (Riggs et al., 1995; Cleary et al., 1996; Marcy and Cleary, 1997). Sand from both the rapidly eroding beach at the headland and the littoral drift, are likely transported seaward of the outcrops during storms and prevented from returning to the beach during subsequent low energy periods. The result of this process is a net sediment deficit.

The shoreline segment that encompasses Carolina Beach and Kure Beach has had a colorful history of stabilization attempts. Erosion of the headland beach as well as the spit extending north of Carolina Beach has been persistent. Borrow sites have been targeted on the shoreface off both Carolina Beach and Kure Beach to mitigate the chronic erosion and to provide storm protection for the area. Kure Beach was recently replenished with fill derived from a borrow site several miles offshore (**Plate**s E-13 and **E-14**). The borrow site is located in the anastomosed channel complex of the ancestral Cape Fear River (USACE, 1993). The Pleistocene channels are estimated to contain a sufficient volume to satisfy the local needs for the next decade and several replenishment cycles.

a. Carolina and Kure Beach Shoreface Characteristics.

The Kure Beach/Carolina Beach subaerial headland shoreface is complex due to several interrelated variables that contribute to the overall nature of this dynamic system. These variables include bathymetry that is dominated by shore-attached sediment ridges and hardbottom areas of varying lithology and relief. The complex bathymetry presumably plays a role in the modification of waves and may impact longshore currents. Cross-shore sediment transport both during and after storm events is also likely to be impacted by these features as well as the abundant hardbottoms.

The shoreface off this area is unlike the traditional smooth concave-upward surfaces. Instead, the presence of shore-attached sand ridges and hardbottom areas result in a very irregular bathymetric signature (**Figures** E-18, **E-19, E-20 and E-21**). The ridges are attached at a variety of angles and local relief may be as much as 1.2-18m. Bathymetric maps and shore-normal fathometer profiles show the largest of the sand ridges lie offshore of the southern portion of the area. In addition to these features, an extensive area of coquina hardbottom occurs seaward of the ridges and extends across the upper shoreface off the extreme southern portion of Kure Beach.

(1). Stratigraphy of the Shoreface.

Snyder et al (1994), Marcy (1997) and Marcy and Cleary (1997), mapped the Kure Beach/Carolina Beach shoreface using high-resolution seismic surveys and showed the region to be dominated by Oligocene and Pliocene outcrops (**Figures E-22 and E-23**). Rock units off this area strike NE and dip gently to the SE (Riggs et al, 1985; Riggs et al, 1990; and Snyder et al, 1994). Overlying these sequences are remnant Quaternary units that combine to form the antecedent topography upon which Kure Beach and the adjacent barrier and headland portions of Carolina Beach are perched (Snyder et al, 1994; Riggs et al, 1995; Cleary et al, 1996).

Snyder and others (1994) and Marcy and Cleary (1997) identified three Quaternary lithosomes that dominate the shoreface. These units represent a variety of coastal lithosome types including Pleistocene calcarenites that form high-relief hardbottoms south of Kure Beach, fluvial sands and gravels that represent paleo-fluvial channel positions, and inner shelf palimpsest and residual sands and gravels (Figures E-22 and E-23).

Tertiary units identified include **t**he early Oligocene River Bend Formation that underlies the shoreface and crops out across the much of the area. It consists of gently sloping clinoform reflectors that prograde SE, or downdip. Diver observations indicate outcrops of this sequenceare commonly low relief, NE striking ridges that are probably bedding planes. These ridges may influence cross-shore transport on a variety of scales. A second Tertiary unit mapped is the Plio-Pleistocene Sequence (PP_{vf}) that is equivalent to the onshore units of the Duplin, Bear Bluff, and Waccamaw Formations (Zarra, 1991; DuBar et al., 1974; and Snyder et al., 1994). These units are resticted to NW-SE trending large valley complexes entrenched into the Oligocene River Bend sequence (Figures E22 and E23). The units form low relief hardbottoms (Marcy, 1997).

Small Quaternary channels are incised into the Plio-Pleistocene as well as the Oligocene River Bend Formation. Some of these channels reoccupy the position of the older Plio-Pleistocene valleys and some are filled with clean fluvial quartz sand, capped by peat. Other channels contain mud.

Diver groundtruthing indicates that locally high-relief regions imaged on seismic profiles were attributable to a well- indurated coquina. This occasionally well lithified unit forms locally high relief features south of Kure Beach. The most prominent of these hardbottoms is locally known as Sheephead Rock (Figure E4). Dockal (1996) correlated the coquina with the Neuse Formation found at Snow's Cut, about three kilometers inland. Offshore of Kure Beach the northern extension of the coquina outcrops are scattered and are generally low-relief. Modern gravelly sands on the shoreface form a mobile cover across the southern portion of the area.

The large shore-attached ridges are relict in nature, and appear to consist of a series of cut and fill features that overlie the larger incised channels and the Oligocene sequence. A number of bathymeterically high, shore-attached ridges occur off both Carolina Beach and Kure Beach. The upper portion of the ridges are composed of alternating units of graded coarse to fine quartz sands and shell gravels. Vibracore data substantiate the seismic data and suggest that some of the ridges are underlain by the Oligocene sequence. In other parts of the shoreface off Carolina

Beach, the ridges are underlain by calcarenite. The relationship of the nature of the underlying units to the occurrence of the ridges is yet to be determined.

The NE-SW orientation of some of the ridges corresponds to the strike of the outcrop patterns of the River Bend sequence. The ridges may be erosional features that mimic the depositional strike of the underlying units. All the major shore-attached ridges on the NE flank of the Cape Fear foreland have the same orientation (Figure E-18). Wave induced and cross-shore currents may also play a role in shaping these features, but to what extent is unknown. It is likely the ridges have complex origins.

(2). <u>Hardbottom Morphology and Distribution.</u>

Two categories of hardbottoms were recognized on the basis of morphology; those of high relief (>0.5 m) and low relief (<0.5 m). The spatial distribution of these types is shown in **Figure E-24**, which is a facies map derived from the interpretation of a sidescan sonar mosaic. Scarps and hardbottom areas covered by mobile sands are also indicated. These sediments are subdivided into coarse and fine sands, and include sand sheets, aprons, and ramps (Marcy, 1997).

There is only one region in the immediate area with relief over 1.0m that may have an impact on the headland area. The area is known as Sheephead Rock, with local relief of more than 3m, located several kilometers south of the southern limit of the Town of Kure Beach (Figure E18). Sheephead Rock significantly affects waves as they approach the shoreline. During periods of moderate swell activity, waves have been observed breaking on this feature. Diver observations indicate that surge occurs on the top of Sheephead Rock even in relatively calm conditions, compared to other areas nearby. The influence of this feature on the adjacent shoreline erosion rates has been documented in a recent study (USACE, 1997). Several post construction shoreline monitoring surveys of the shoreline reach south of the Forth Fisher seawall show that the segment of shoreline in the lee of the feature has lower annual erosion rates than adjacent reaches, all of which are downdrift of the seawall.

Sidescan sonar data and fathometer traces across the Sheephead Rock area indicate that this high area is an irregular surface dominated by a series of rock ridges, some of which are 3m in height. In between the ridges are irregular shaped depressions that are often filled with sediment. The calcarenite sequence that forms this feature extends north to Kure Beach and beyond. A sidescan sonar mosaic shows a similar series of ridges and depressions off southern Kure Beach that are capable of trapping or at least influencing cross-shore sediment transport. It is difficult to determine if this large-scale karstic mosaic had any direct influence on the storm's impact along the headland segment of Kure Beach.

At Fort Fisher the coquina forms a small wave-cut platform which extends beneath Kure and Carolina Beaches as well as adjacent Masonboro Island to the north (Plate E-10). The unit continues offshore and underlies some of the shore-attached ridges. Most often it is highly weathered and forms relatively low relief hardbottoms over much of the shoreface (Figures E-20-E-23). Moorefield (1978) and Riggs et al, (1995) indicated that the irregular topography associated with this unit is instrumental in trapping littoral materials and redirecting sediment across the shoreface off Fort Fisher and Kure Beach.

Hardbottoms of less than 0.5m of relief are areally extensive. The flat, low relief undulating hardbottoms are locally important as a sediment contributor, but their role in influencing cross-shore sediment transport is conjectural. These low relief areas are more difficult to observe and map because they are periodically covered by migrating sand sheets.

Two dominant rock types form low relief hardbottoms; the Plio-Pleistocene moldic limestone and the Oligocene dolosilt. Compared to the high-relief hardbottoms south of Kure Beach, these rocks are much older and less resistant to erosion. The moldic limestone is composed mainly of shell rich grains in a homogenous microcrystalline calcite matrix. The dolosilt has a homogenous composition consisting of fine angular quartz grains and a dolomitic cement. Both of these units produce flat hardbottoms that are intermittently covered by modern sediment.In the vicinity of Kure Beach, there appears to be linear hardbottom ridges and scarps striking NE (Figure E-24). Core data, diver observations, and seismic profiles indicate that these ridges are composed of the Oligocene dolosilt. These ridges are less than 0.5m high but may influence sand transport on the upper shoreface.

(3). Surface Sediment.

On retreating coasts, such as Carolina and Kure Beaches, the shoreface is a major source of new sediment, via mechanically and biologically related erosion. Biological erosion occurs as the result of a combination of factors that serve to degrade the rock. Mechanical erosion occurs in response to coastal and shoreface processes often triggered by storm events. The modern sand veneer is patchy and easily mobilized during storms, exposing strata on the shoreface to erosion (Niedoroda et al., 1985; Cleary et al., 1992; 1996). Hardbottoms provide an immediate source of "new" sediment, made ready by burrowing and boring organisms.

The acoustic backscatter signature of the sidescan sonar data (Figure E-24) suggests there are two prevalent types of surface sediment. Diver mapping exercises and core data indicate fine to medium sand and medium to coarse sand and gravel are generally the two most common surface sediment types. The majority of the coarse sands and gravels are situated close to hardbottom areas. Other areas of coarse sediments are associated with incised paleo-fluvial channels (Figures E-22 and E-23).

It is significant to note that in the areas of hardbottoms, the carbonate and gravel percentages are both high. This relationship occurs across the shoreface and indicates that a majority of the gravels on the shoreface are carbonate material derived from erosion of hardbottoms. The majority of surface sediments are sand to gravely sand. The sediments in close proximity to coquina outcrops contain a higher percentage of gravel than sediments near other hardbottom lithologies (Marcy and Cleary, 1997). This is probably related to the resistant nature of both the carbonate and clastic components in the coquina. In general, the coquina derived sediments were poorly sorted, while sediments fronting the Oligocene dolosilt and Plio-Pleistocene limestone scarps were moderately to well sorted.

Insoluble residue analyses of the Pleistocene coquina that forms Sheephead Rock indicate it is composed of 58% insoluble material, consisting mainly of coarse sand and quartz pebbles and gravels. In contrast, the Plio-Pleistocene moldic limestone consists principally of small amounts of very fine quartz silt (9.2%) and clay. Oligocene dolosilt samples contain 31% angular quartz silt and fine sand-sized particles. These data indicate that hardbottoms may potentially contribute significant amounts of material to the shoreface. Although the coquina is much less areally extensive than the Oligocene dolosilt, it probably plays a greater role as a source for "new" sand sized particles and larger carbonate grains. The great majority of the coarse carbonate fraction found on the adjacent beaches is derived from this unit. All of the beaches and washover fans from southern Masonboro Island to New Inlet are littered with large coquina clasts after every major storm event.

Also exposed are several paleo-fluvial channels (Figures E-22 and E-23). These channels are infilled with clean, angular, muscovite-rich, quartz sand and gravel with a Piedmont signature. Reworking of these channels must have contributed a significant amount of sand and gravel to the system. Evidence of reworking is confirmed by diver observation and surface sediment samples (Marcy, 1997).

D. INFLUENCE OF THE GEOLOGIC FRAMEWORK

1. OVERVIEW.

The coastwise variability in storm response and the subsequent beach recovery was influenced by a variety of site specific factors including the geologic framework. Some segments of the beaches that comprise the six study sites are thin modern sand units perched on top of older sediments and strata of varying age and lithology. The thickness of the modern beach prism varies among the study sites and is thinnest along the headland segments (North Topsail Beach and Carolina/Kure Beaches).

The pre-storm condition of the sites to a large extent controlled the storm's impact (foreshore retreat, overwash, and structural damage) and recovery. The recent erosion history and consequent shoreline morphology of each of the sites was a byproduct of the interplay of a variety of site specific variables. These variables include the long and short-term erosion trends and the replenishment history of the various segments. Offshore variables include the shoreface geometry, availability of sediment, as well as hardbottom morphology which impacts wave setup, refraction and cross and longshore currents. The interplay between the hardbottom character and storm generated waves and bottom flows probably controlled the magnitude of cross-shore transport and ultimately the shoreline recovery trends. The aforementioned site-specific variables coupled with the meteorological characteristics of Hurricanes Bertha and Fran determined the observed patterns.

When dealing with the time-scale involving individual storm events, such as the hurricanes of 1996, it is clear that the importance of the geologic heritage varied greatly along the impact area. In most cases the underlying geologic framework exerted a negligible influence on the storm's impact. **Table E-1** lists the various attributes and characteristics of the study areas. The interplay amongst the factors identified is discussed in the following sections dealing with regional aspects as well as local conditions.

Table E1: Shoreface Characteristics

Characteristic of the Study Site	Kure Beach	Carolina Beach	Wrightsville Beach	Topsail Beach	Surf City	North Topsail Beach
Hardbottoms	Moderate	Moderate	Moderate	Moderate	Moderate	Extensive
Age and Lithologh	Pleistocene-Oligocene (Coquina-siltstone limestone	Pleistocene-Oligocene (Coquina-limestone siltstone)	Pliocene-Oligocene (Limestone siltstone)	Oligocene (Limestone)	Oligocene (Limestone)	Oligocene (Limestone)
Morphology Relief	Flat to low relief	Flat to low relief	Flat to low relief	Flat to low relief, less than 1.0cm	Flat to low relief, less than 0.5cm	Flat to moderate (up to 2.0m)
Shore Attached Ridges	Extensive	Extensive	Minor	Absent	Absent	Absent
Other Features	Shore-Oblique rock scarps	Shore-Oblique rock scarps	Ripple-scour depressions	Minor ripple scour depressions	?????	Shore normal linear channel-like features, multiple landward facing scarps
Paleo Channels	Major	Major	Minor	Minor	Few	Few
Sediment Cover	Moderate	Moderate	Moderate	Moderate	Thin	Absent
Pre-storm Beach Condition	Scarped dune topographic high beach	Artificial beach except along northern segment	Beach fill	Scarped beach, artificial dune, scarped along S. portion	Low dunes, often scarped along N. 2/3 of town	Low to non-existent dunes
Underlying Geologic Units Beneath Shoreline/Surf Zone	Humate SS Coquina	Humate SS Lagoon material along northern segment	Sand	Sand, peat/lagoons	Sand	Variable sand, dense clay peat
(Geol. History) Upper Shoreface	Subaerial headline	Subaerial headline	Inlet fill	Inlet fill / transgressive barrier	Inlet fill	Perched barrier submarine headland transgressive
Renourishment History	None	Frequent	Frequent	Minimal	None	None
Overwash	Minimal	Minimal to moderate along N. segment	Minimal to extensive (Moore's Inlet zone)	Extensive to minimal along N. segment	Extensive to minimal along S. segment	Extensive
Structure Damage	Moderate	Moderate along northern end	Minimal (except near Old Inlet)	Severe oceanfront Moderate 2nd row	Severe oceanfront	Severe oceanfront

E. SUMMARY OF SITE SPECIFIC CONTROLLING FACTORS

1. NORTH TOPSAIL BEACH.

North Topsail Beach comprises the northern 18.7km of Topsail Island. Much of this barrier segment is influenced by the New River submarine headland and as a result the modern barrier sand prism is relatively thin (< 2.0m). The barrier is perched on top of a variety of older materials including peat, lagoonal mud and compact Pleistocene mud. The extensive outcrops of peat and cedar stumps along much of the central portion of this shoreline segment testifies to the very low volume of material comprising the barrier platform.

Cores, aerial photographic data and vegetation patterns indicate the majority of this shoreline reach has been a chronic washover zone for the past several centuries. The high susceptibility to repeated overtopping suggests the vulnerability of this area is related to a lack of significant recovery between events. The 1996 pre-storm condition of the beach played a direct role in the severity of the damage and the extensive erosion recorded along North Topsail Beach. The pre-storm condition was related to the scarcity of sand in the hardbottom dominated nearshore system.

The factors that were instrumental in the long and short-term erosion and morphologic development of much of the northern section of Topsail Island can be related to the geologic nature of the shoreface. The morphologic expression of the submarine headland in the form of extensive moderate relief hardbottoms probably played a significant role in both the storm's impact and the shoreline recovery over the short and long-term. The regional limestone platform-like feature along with the localized bathymetric highs (scarps) must have influenced the incident waves and storm-generated currents along and across the shoreface. Over the recent geologic past these features have played a significant role in the morphology of Late Holocene as well as modern barriers in this area of Onslow Bay.

The geometry and composition of the hardbottoms has also affected the recovery of the shoreline, not only after the storms of 1996, but previous events as well. The irregular karstic surface that comprises the shoreface is composed of a series of irregularly spaced, landward facing scarps and intervening plateaus or depressions. The northern portion of the shoreface north of Alligator Bay has more numerous and higher relief scarps. This segment of the shoreface has little to no sediment cover and lies adjacent to the shoreline reach that experienced the greatest damage and the most severe erosion and overwash. The bathymetry of the central and northern portion of the shoreface off North Topsail Beach shows several shore normal topographic lows that extend across much of the shoreface. These linear channel-like features are constrained by topographically high hardbottoms and may represent solution features that have been modified by fluvial processes during low stands of sea level. Regardless of origin, they appear to act as conduits for cross-shore transport of material to the inner-shelf. The graded storm sequence recovered from beneath these conduits is covered by a mosaic of migrating ripple fields. The loss of sediment via these channel-like areas and the trapping ability of the numerous irregularly spaced scarps precludes shoreline recovery along this area.

The durability and quartz-poor nature of the limestone units that form the extensive outcrops does not lend itself to the production of large volumes of new sand-sized sediment by shoreface processes. The orientation of the shoreline and the frequent storms that impact this sediment-starved shelf sector have combined to produce a barrier segment that is poised to migrate rapidly. The rollover is directly related to the storm history and the geologic nature of this morphologically unique shoreface.

2. SURF CITY.

Surf City, occupying the central portion of Topsail Island, was one of the most severely impacted shoreline reaches within the impact area. The low-lying barrier in this area fronts an extensive 200 year-old vegetated flood tidal delta. The pre-storm beach was characterized by low relief, scarped and often discontinuous, foredunes. The sand prism that comprises this section of the barrier is relatively thick (8-10m). The lower portion of the barrier platform along much of this area overlies a sequence of inlet fill associated with Stumpy Inlet and pre-historic inlets. Lagoonal muds and peat underlie the northern and southern extremities of Surf City.

It is interesting to note that the worst damage and overwash occurred along the shoreline stretch that fronted the most recent position of the wide and ephemeral Stumpy Inlet. The 4.5km long barrier shoreline segment south of the old inlet, as well as portions of the shoreline north of Surf City, were the site of the only minor overtopping, although dune erosion did occur. These aforementioned areas, where overwash was confined to topographically higher oceanfront areas, may represent the former inlet's shoulders where larger, wider and older dune fields are present. One can speculate that the closure of the old inlet led to planform (island curvature) changes. Following the closure of the former breach this area did not develop a significant dune field due to a lack of a suitable sediment source.

The erosion history over the past decade has resulted in a narrowing of the foredune along the former inlet zone. Furthermore, development in the area has lead to the removal and alteration of the character of the low relief backbarrier dune field, which has increased the hazard potential.

It is unlikely that the geology of the shoreface had a significant effect on the storm's impact in this area. The offshore area beyond depths of 8-9m is characterized by extensive low relief hardbottoms mantled by a patchy veneer of fine sand of variable thickness. The Oligocene limestone that is exposed across the shoreface is extremely indurated and is not a major contributor of new sediment to the overlying modern sediment cover in the long-term. However, some contributions from the hardbottoms were evident along the post-storm beach that was littered with extensive coarse sand and limestone clasts derived from the immediate offshore area.

No detailed morphologic information about the shoreface morphology exists for this area. Fathometer profiles indicate that the shoreface off Surf City, seaward of 8-9m water depth, is marked by occasional low relief landward facing scarps and flat hardbottoms. The exact role the geologic framework played in the storm's impact on this shoreline segment and the subsequent beach recovery is difficult to determine.

3. TOPSAIL BEACH.

Topsail Beach comprises the southernmost 7.2km of Topsail Island. The southern 11km segment of Topsail Island is a variable relief spit that has extended to the south during the migration of New Topsail Inlet over the past 300 years. The barrier platform's sand prism is relatively thick consisting of an 8-11m sequence comprised of inlet fill, beach, washover and dune sediments. The southern 2km section of this shoreline reach has been a chronic erosion zone and the site of extensive overtopping during recent storms. The erosion stems from the realignment of the shoreline (Topsail Beach) as the inlet migrated to the southwest. The attendant planform changes have led to dramatic changes over the past 20 years.

As a result of the inlet's influence on the updrift barrier planform, small-scale replenishment projects that have been undertaken have had little chance of success in mitigating the erosion. Although a small artificial dune and berm was in-place during the summer of 1996, it did little in the way of mitigating storm-related erosion and extensive overwash. The morphologic changes and structural damages that did occur are related more to the pre-storm condition of the barrier than to the geologic controls.

The shoreface off Topsail Beach is similar to the area off Surf City. Much of the nearshore area, out to depths of 10-14m, consists of Oligocene limestone and siltstone hardbottoms with a thin (<1.0m) veneer of silt and fine sand. The shoreface morphology is generally flat with occasional 1.0m scarps. It is unlikely that this type of shoreface geometry played a significant role in the storm's impact on the adjacent beach.

4. WRIGHTSVILLE BEACH.

Wrightsville Beach is a 7.3km long barrier island composed of two former barrier segments. Data show the entire barrier is underlain by inlet fill deposited during the past several hundred years. As a result, the barrier platform is relatively thick in comparison to the modern beach on the headland influenced shoreline segments. In this area modern sand sequences are up to 10m thick. Beneath the basal inlet sequence are early Holocene lagoonal muds, compact Pleistocene muds and older limestone units.

The majority of the significant overwash and the limited structural damage occurred within the chronic erosion zone that developed along the mid barrier shoreline bulge. Other sections of Wrightsville Beach, located south of Mercer's Pier and the shoreline bulge, were impacted only slightly. Much of the remaining portions of Wrightsville Beach south of old Moore's Inlet has been frequently renourished. As a result, much of the barrier was characterized by a relatively wide artificial beach/dune system during the summer of 1996. Overwash and erosion was limited along almost the entire southern section of the beach. Similarly, along the shoreline reach north of old Moore's Inlet, dune erosion occurred but for the most part overwash was restricted to the breaks within the foredune and within the dune swales. Little structural damage occurred along the northern part of Wrightsville Beach (Shell Island).

The numerous shore-normal rippled scour depressions that are characteristic of the shoreface off Wrightsville Beach and the scattered hardbottom areas in all likelihood did not play a significant role in determining the impact of the 1996 hurricanes on the Wrightsville Beach shoreline. However, the coastwise shape of the shoreline coupled with cross-shore morphology may have been responsible for the seaward transport and loss of an unknown volume of beach material during the storms. The cumulative effect of this asymmetric cross-shore flux lead to a historical sediment deficit that translated into net shoreline retreat. The large volume of beachfill frequently placed along the shoreline during the past four decades helped to offset the above-mentioned loss.

Historic aerial photographs of Wrightsville Beach dating from the late 1920's and early 1930's clearly show numerous groins and bulkheads indicating that erosion was rampant along the entire barrier. The island was exceptionally narrow with a poorly developed foredune. It is surprising that Hurricane Hazel (1954) did not cause more damage when one considers the poor condition of Wrightsville Beach in the early 1950's. Aerial photographs suggest that North Topsail Beach had a healthier beach/dune system in the early 1980's than Wrightsville Beach did before the landfall of Hurricane Hazel in October 1954. Without the extensive restoration that has occurred since the mid 1960's, the impact of Hurricane Fran on Wrightsville Beach would have been extreme, and likely worse, than the damage recorded along Surf City and North Topsail Beach.

5. <u>CAROLINA AND KURE BEACHES</u>.

Carolina Beach is comprised of two distinct morphologic components. A barrier spit forms the northern 4.9km of shoreline. Approximately 2.7km of the southern portion of the barrier is developed. The northern 1.1km of the developed section is fronted by rip-rap. The remainder of the spit that extends to Carolina Beach Inlet is undeveloped and is highly susceptible to overwash. The subaerial headland portion of Carolina Beach extends approximately 1.5km in a southerly direction to the northern limits of the Town of Kure Beach. The modern sand prism along this portion of the barrier ranges from 4.0 to 7.0m in thickness. The basal portion of the thicker sequences is comprised of isolated pockets of inlet fill. The thinner sequences are located along the undeveloped spit section where lagoonal mud and peat outcrops are found along the foreshore area north of the rip-rap.

The Town of Kure Beach, along with the Fort Fisher enclave, is located along the remainder of the subaerial headland. These headland beaches are comprised of very thin units (<2-3m) of modern sand resting on Pleistocene units of calcarenite or friable humate sandstones. Post-storm photographs clearly show the perched nature of this headland reach. While the modern beach is indeed very thin the higher elevations associated with the old headland topography probably helped reduce the impacts of the elevated water levels and associated overwash.

The majority of overwash and severe structural damage that occurred along Carolina Beach was restricted to the northern portion of the developed section in the vicinity of the rip-rap. This chronic erosion zone has historically been subject to frequent overtopping during storms since the emplacement of the rip-rap in the late 1960's and early 1970's. Erosion of the artificial dune and berm did occur along the remainder of the Carolina Beach oceanfront to the south but overwash and structural damage was very minimal. Overwash was restricted to the dune walk-overs and along the low, flood-prone section near Carolina Lake, a turn of the century inlet zone.

Moderate storm damage and overwash occurred along the topographically higher Kure Beach oceanfront. Shoreline recession damage to the oceanfront homes was related to the lack of a wide beach and dune system. Because the backshore area is topographically high overwash and structural damage was restricted to the oceanfront.

The complex bathymetry of the shoreface off this headland influenced shoreline segment stems from the development of the large relict NE trending shore attached ridges on top of the hardbottoms of varying lithology and relief. Although hardbottoms are widely distributed across this headland shoreface, scarps appear to be more numerous and of higher relief along the southern portion of the headland off the Kure Beach upper shoreface. The higher relief and more frequent scarps in the southern portion of the area probably played a minor role in the initial impact of the storm. The degree of recovery that might have taken place was masked by the artificial manipulation of the beach profile. The amount of recovery that would have occurred in this reach is open to question. It is likely that forebeach buildup would have taken place but it would have been limited due to the complex offshore bathymetry.

Along Carolina Beach natural recovery was probably limited to forebeach accretion involving material returned to the beach from the offshore area down to depths of approximately 8m. The pre-storm condition of this entire shoreline reach coupled with the convoluted nature of the upper shoreface and the morphology of the hardbottoms, must have impacted the surge elevations and dictated transport pathways across the uplands and shoreface.

Much of the sediment cover in this area is derived from the degradation of the coquina hardbottoms and the reworking of the paleo-channels that are incised into the bedrock. Although this shoreface generally has more sediment cover than North Topsail Beach or Surf City, long-term natural recovery of the shoreline is highly unlikely given its erosion history and the complex nature of the shoreface.

F. THE GEOLOGIC FRAMEWORK AND THE SHOREFACE PROFILE

The shoreface is the link that couples the shoreline and the inner continental shelf. This complex environment can act as a source, barrier or avenue for bi-directional transport of materials between the beach and the deeper offshore areas. The geologic and oceanographic processes operating across this environment play a variable role in determining how a shoreline reach will respond to individual storms and the collective impact of storms over the long term.

The shoreface has traditionally been thought to be sand rich and achieve an equilibrium shape related to wave climate and surficial sediment grain size (Bruun, 1954; Dean, 1977 and Zeidler, 1982). An equilibrium profile equation was first proposed by Bruun (1954 and 1962).

Bruun (1962) used this equation to develop a simplistic model for coastal evolution, in which a constant profile shape translates landward and upward in response to sea-level rise. Dean (1977 and 1987) later focused on the importance of grain size in describing shoreface response and evolution. The concept of an equilibrium profile relies on several important assumptions about the nature of the shoreface and processes that are not consistent with most shoreface systems (Pilkey et al., 1993 and Thieler et al., 1995). The concept has been accepted as valid and is a fundamental principle behind most analytical and numerical models of shoreline change used to predict shoreface/shoreline behavior (e.g., Hansen and Lilycrop, 1988, Hanson and Kraus, 1989 [the GENESIS model], Larson and Kraus, 1989).

The complex geology of the six sites, particularly the headland shorefaces, does not lend iteslf to the application of equilibrium profile-based models. In addition to the fact that most shorefaces are dominated by patchy hardbottoms of varying relief, there is a lack of a consistent grain size across the profile and therefore grain size variations are too complex to be described by simple equations and parameters. It is not uncommon for the grain size to vary from silt to boulders within a distance of several meters in the vicinity of hardbottoms.

In southeastern North Carolina the geologic framework is the predominant control on shoreface profile shape. On these shorefaces, the stratigraphic framework controls outcrop patterns, hardbottom distribution, bathymetry, and ultimately sediment characteristics. The shapes of these bedrock-controlled shorefaces are further complicated off the headland reaches by the relict ridges and karst topography inherited from previous lower stands of sea level. The resulting bathymetric signature is not characterized by shore-parallel isobaths, and therefore does not lend itself easily to numerical modelling.

During individual storm events cross-shore transport of sediment on these hardbottom dominated shorefaces is more complex than would be envisioned by simple shoreface equilibrium models. Although the influence of the hardbottoms on cross-shore transport is yet to be determined, one can speculate that in areas where sediment cover is very thin and hardbottom relief is relatively high, their impact on the benthic boundary layer structure and bed shear stress must be substantial.

Off North Topsail Beach, the bottom morphology and bed roughness related to the irregular spacing and relief of the scarps, coupled with the patchy nature of the corrugated, flat, algal-encrusted hardbottoms, dictated the ultimate shoreline erosion patterns and the direction and volume of sediment transport. Along the intra-headland barrier segments of Surf City, Topsail Beach and Wrightsville Beach the role of the underlying geologic framework was minimal. In a relative sense the shoreface geology off the headland segment at Carolina/Kure Beach, characterized by numerous low relief ledges, flat hardbottoms and large shore-attached ridges, played a moderate role in dictating the observed erosion and recovery patterns.

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Final Report
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HURRICANE IMPACTS AND BEACH RECOVERY IN SOUTHEASTERN NORTH CAROLINA: THE ROLE OF THE GEOLOGIC FRAMEWORK

by

William J. Cleary

22 April 1999

LIST OF FIGURES

Figures

Figure E-1 Location Map

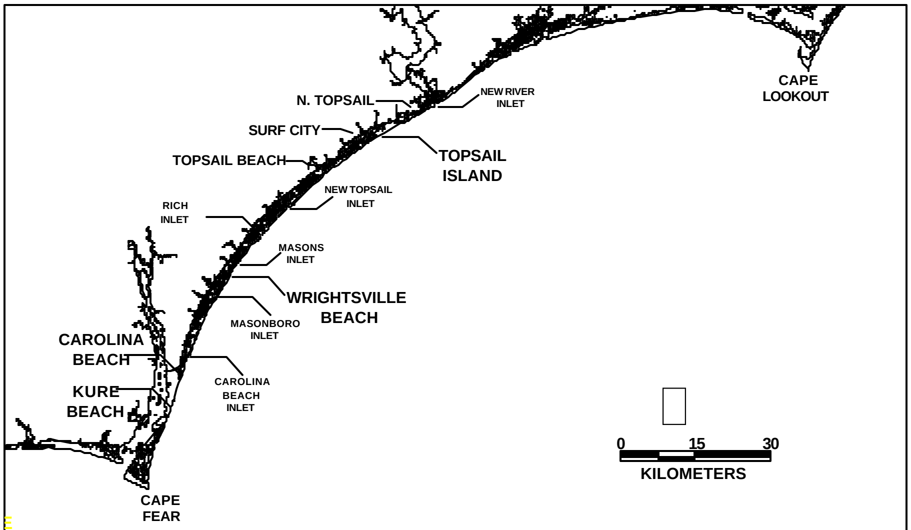
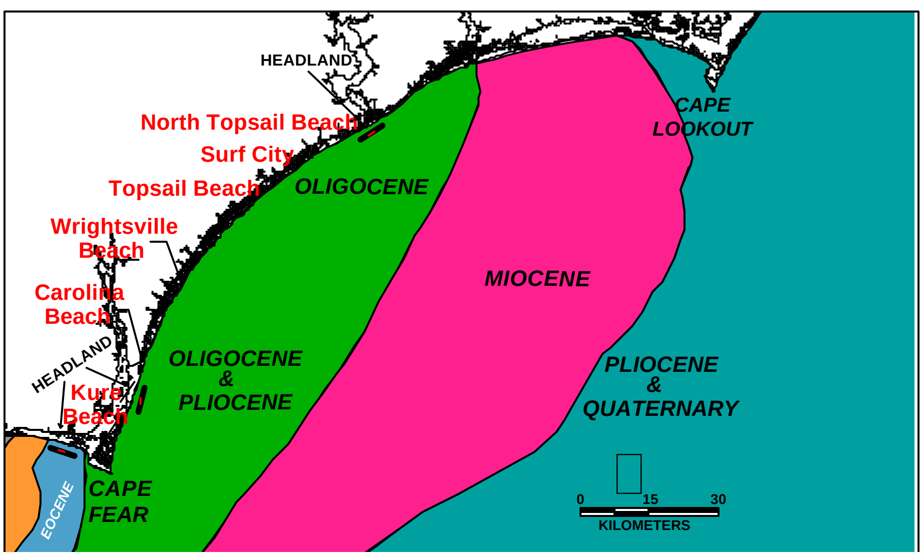


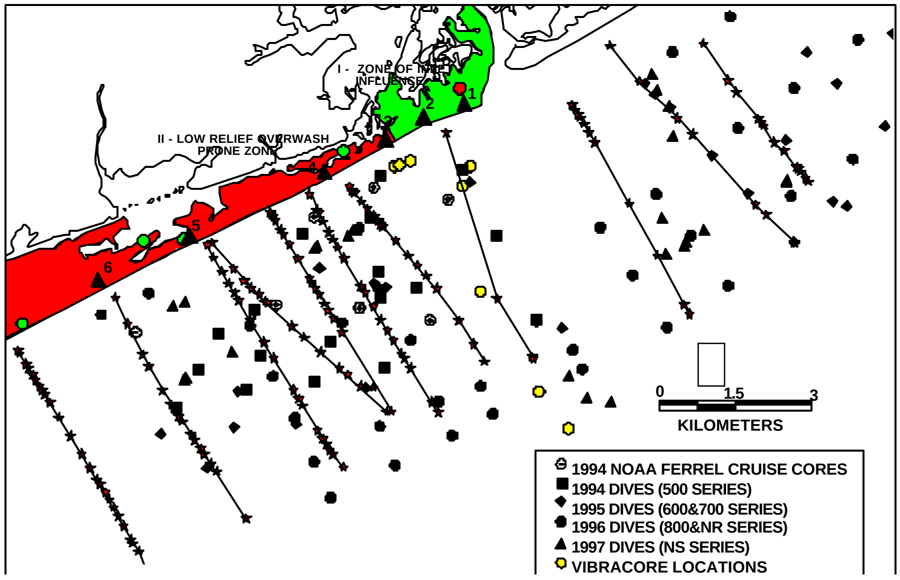
Figure 1. Location map depicting the four study sites and adjacent environments.

Figure E-2: Generalized Geologic Map



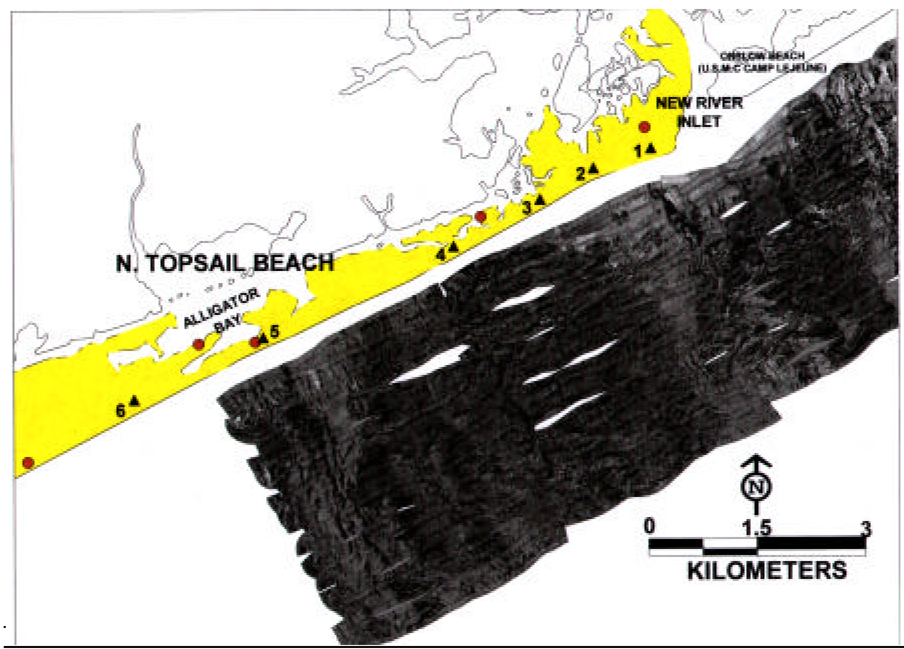
Generalized geologic map of the continental shelf (after Snyder, 1982). Study sites are fronted primarily by Oligocene units that are often incised by channel complexes of varying age. Headland areas are also shown. Pleistocene units crop out across much of the shoreface from south of Fort fisher to Masonboro Island.

Figure E-3: North Topsail Island Beach and Offshore Area



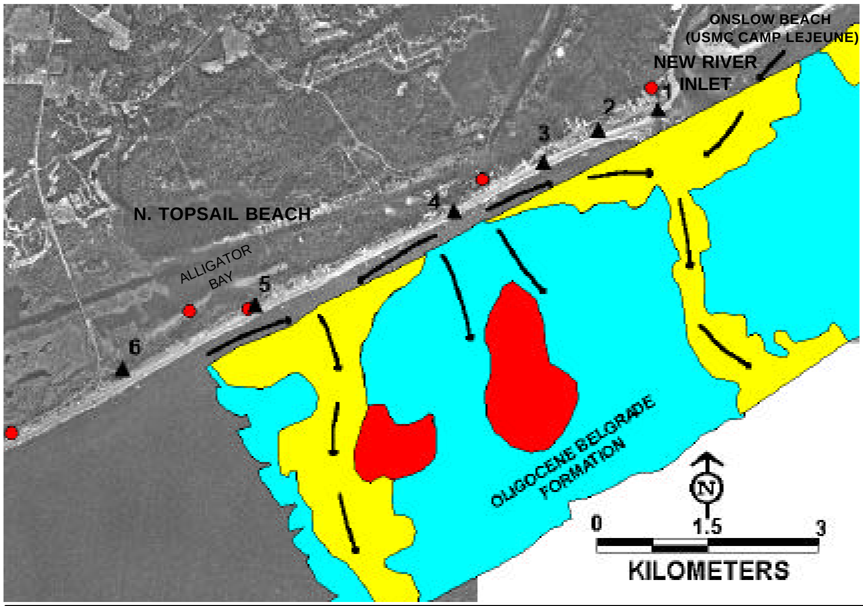
Map depicts core, sample and fathometer profile locations.

Figure E-4: Sidescan Sonar Mosaic of North Topsail Beach Shoreface Area



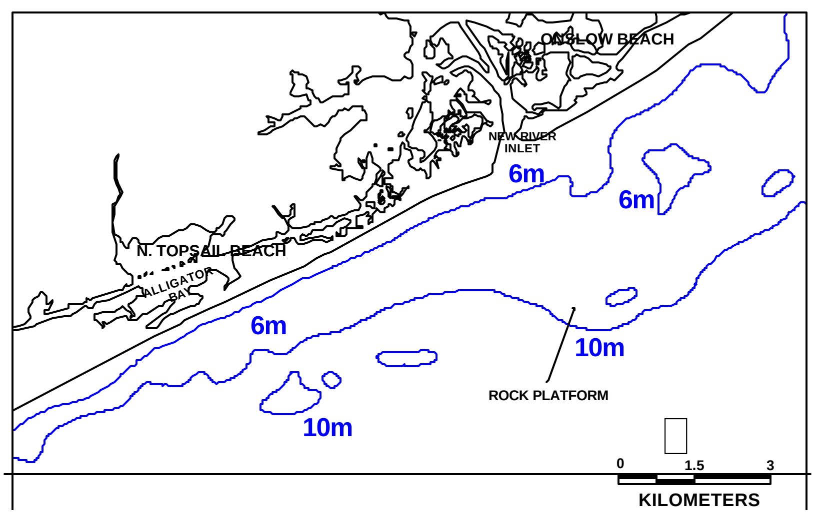
Locations of split-spoon cores along the barrier are indicated by dots and beach profile stations are referenced by triangles. See figure E-5 for interpretation (after Johnson, (1998).

Figure E-5: Map Depicting Interpretation of Sidescan Sonar Mosaic



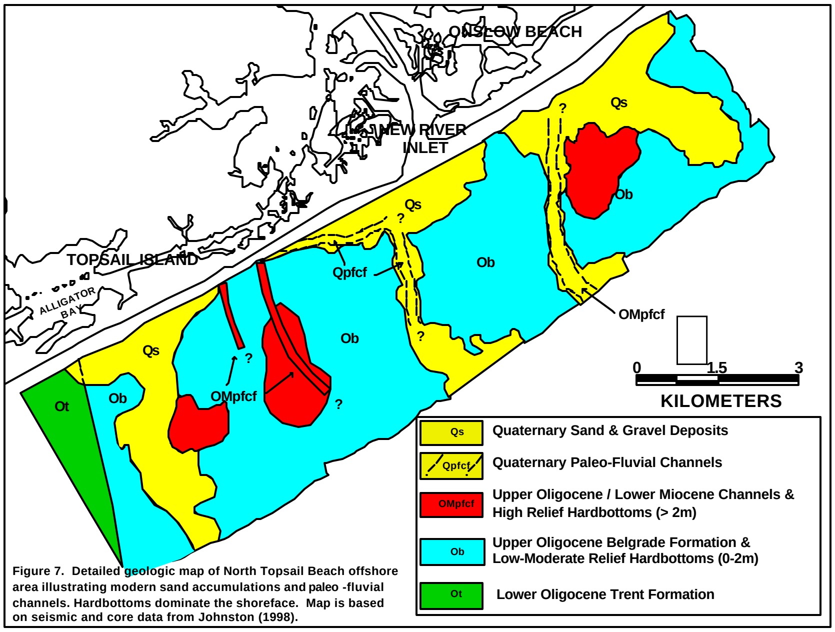
Map depicting interpretation of sidescan sonar mosaic (Figure E-4), core locations and beach monitoring stations (after Johnson, 1998). Light areas delineate accumulations of modern sands and gravels. Medium background represents low relief limestone hardbottoms. Dark areas are high relief (1-2m) hardbottoms. Low areas Rae topographic depressions that lie seaward of saddles within the limestone that underlies the barrier.

Figure E-6: Bathymetic Map of North Topsail Beach and New River Inlet



Bathymetric map of the area around North Topsail Beach and New River Inlet. Note platform-like feature that occurs off the inlet and the excursion of the contour lines. This feature influenced the shoreline conditions and processes throughout the Holocene and Pleistocene.

Figure E-7: Detailed Geologic Map of North topsail Beach Offshore Area



Detailed geologic map of North Topsail Beach offshore area illustrating modern sand accumulations and paleo-fluvial channels. Hardbottoms dominate the shoreface. Map is based on seismic and core data from Johnson (1998).

Figure E-8: Fathometer Profiles off North Topsail Beach

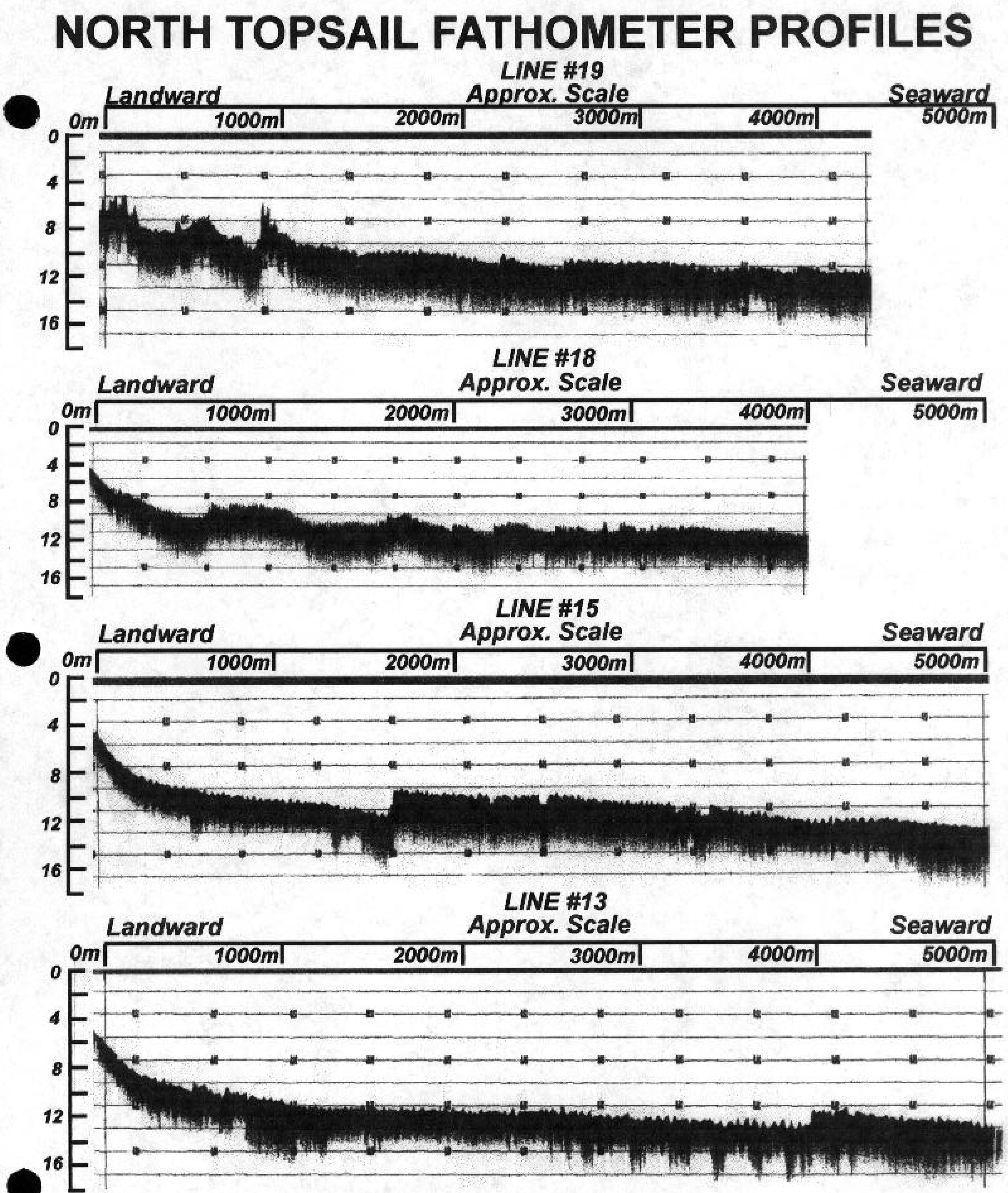
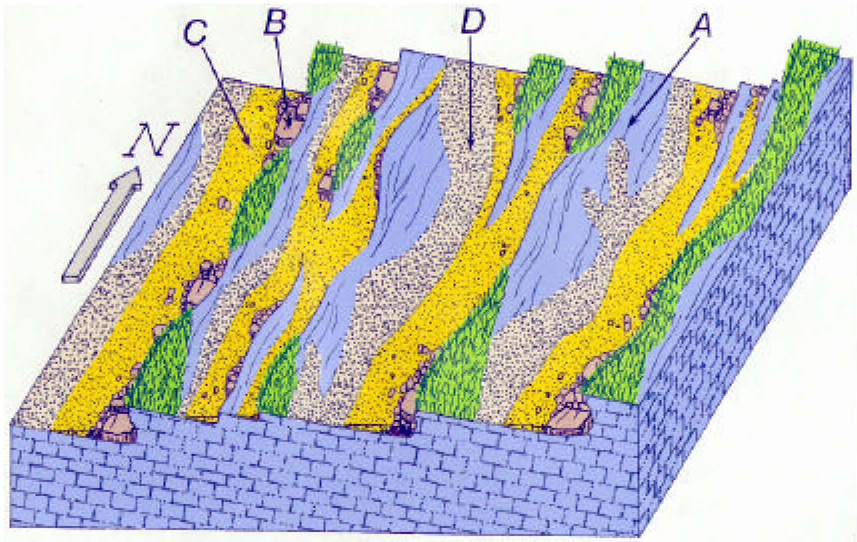


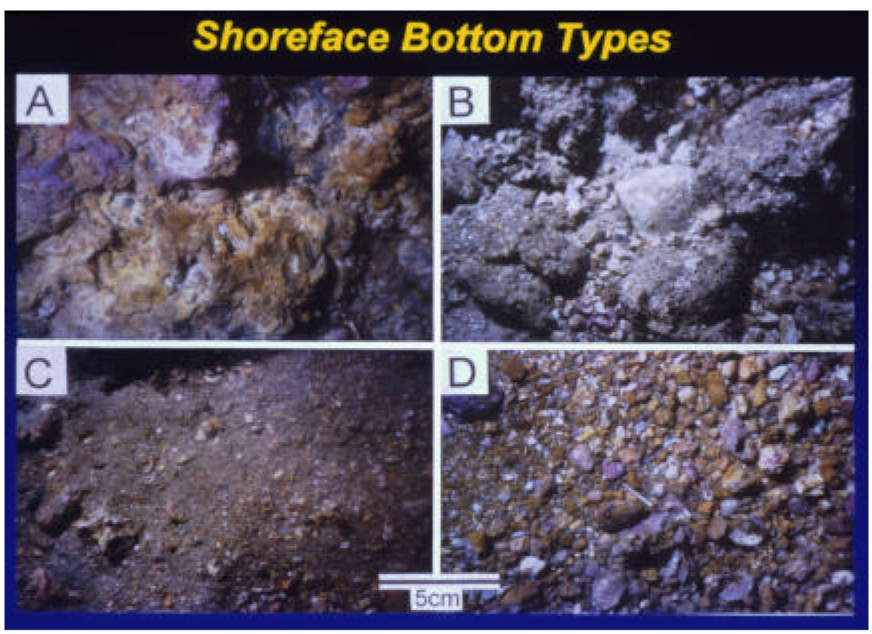
Figure 8. Representative fathometer profiles off North Topsail Beach. Note the many scarps that play a role in the cross-shore movement of sediment. See Figure 2 for locations of profiles.

Figure E-9: Cartoon Depicting Hardbottom Scarps



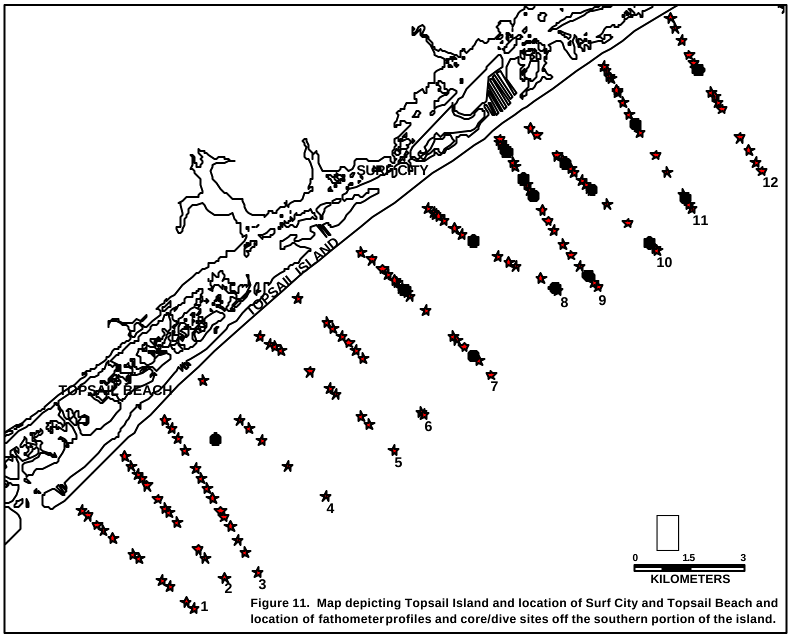
Cartoon depicting the relationship of the hardbottom scarps, landward-facing ledges and the modern sediments (after Johnson, 1998). The schematic represents a typical hardbottom area between the topographic lows that act as corridors for sediment movement. Designations A-D refer to locations of photographs depicted in Figure E-10.

Figure E-10: Hardbottom Photographs of Hardbottom Areas Depicted in Figure E-9



Bottom photographs of hardbottom areas depicted in Figure E-9. A) Algal encrusted Oligocene limestone typical of flat surfaces. B) Typical rubble that fronts scarps. Material is derived in part from collapsed overhangs. C) Carbonate-rich sand often abut toe of rubble and scarps. D) Coarse gravels that underlie the sands depicted in "C". Sediments appear to move laterally along the scarps.

Figure E-11: Location of Fathometer Profiles and Core/Dives Sites off Topsail Island



Map depicting Topsail Island and location of Surf City and topsail Beach and locations of fathometer profiles and core/dive sites off the southern portion of the island.

Figure E-12: Fathometer Profiles off Surf City

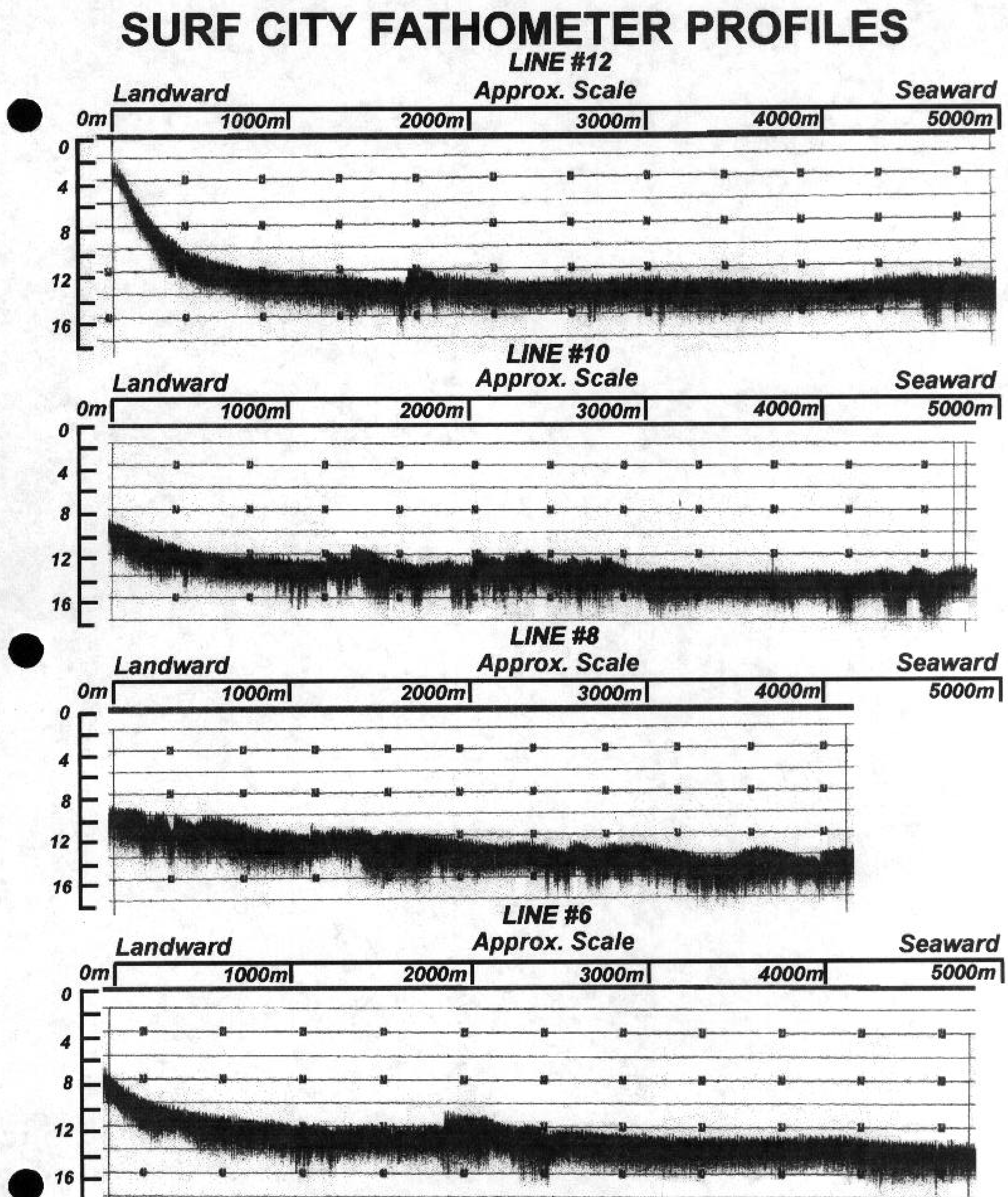


Figure 12. Fathometer profiles off Surf city. See Figure 11 for locations. Lines 6-12 show evidence of multiple scarps and hardbottoms. Most scarps are landward facing and often fronted by sediment aprons.

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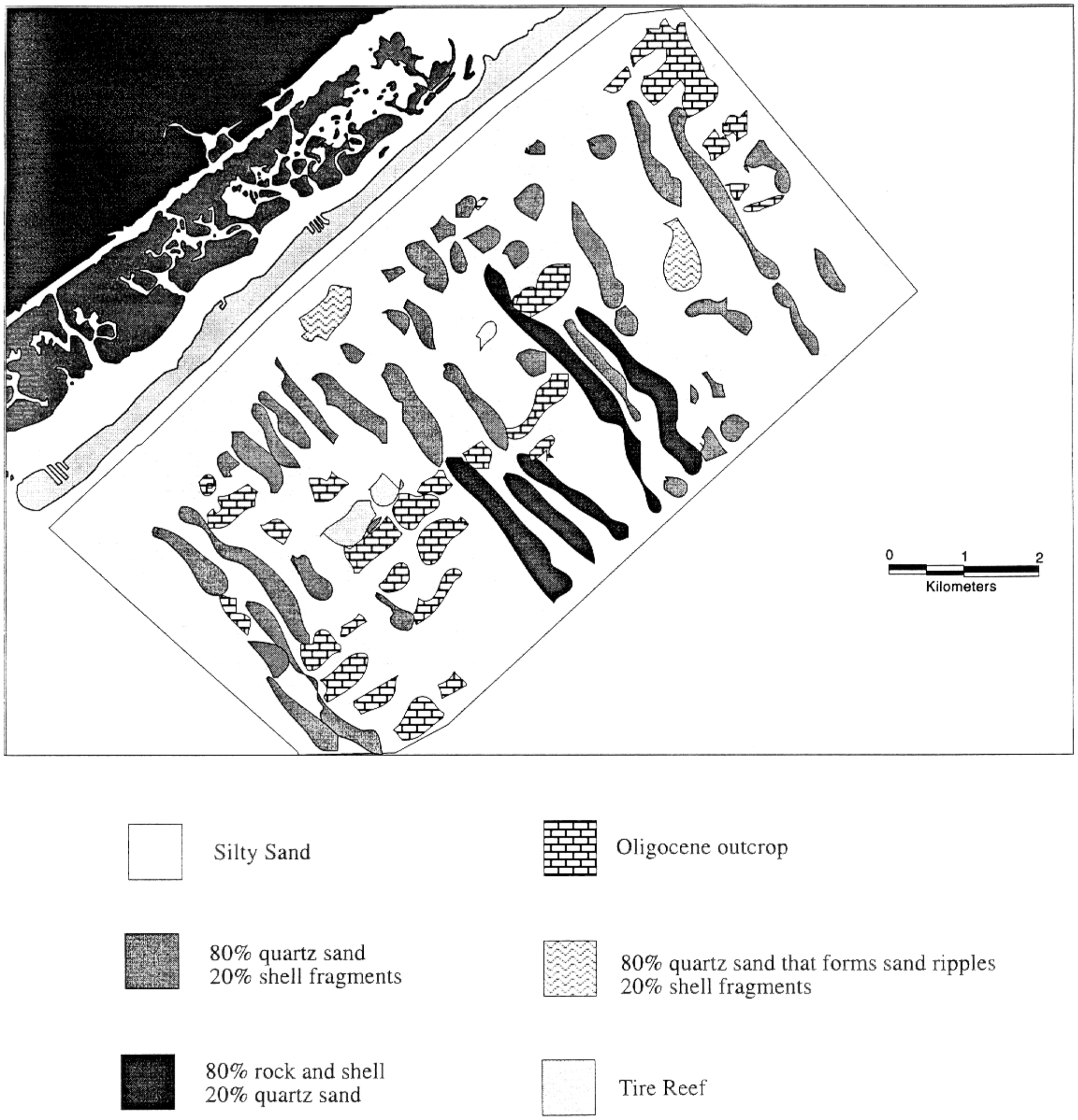
Figure E-13: Facies map of Shoreface off Topsail Beach



Facies map of shoreface off Topsail Beach. Map is based on interpreted sidescan sonar mosaic. Surficial sediment cover consists of a thin (0-1.0m) layer of silty quartzose sand that overlies Oligocene units. Elongated regions of coarse material are interpreted to be discontinuous channels (after McQuarry, 1998).

Figure E-14: Fathometer Profiles off Topsail Beach

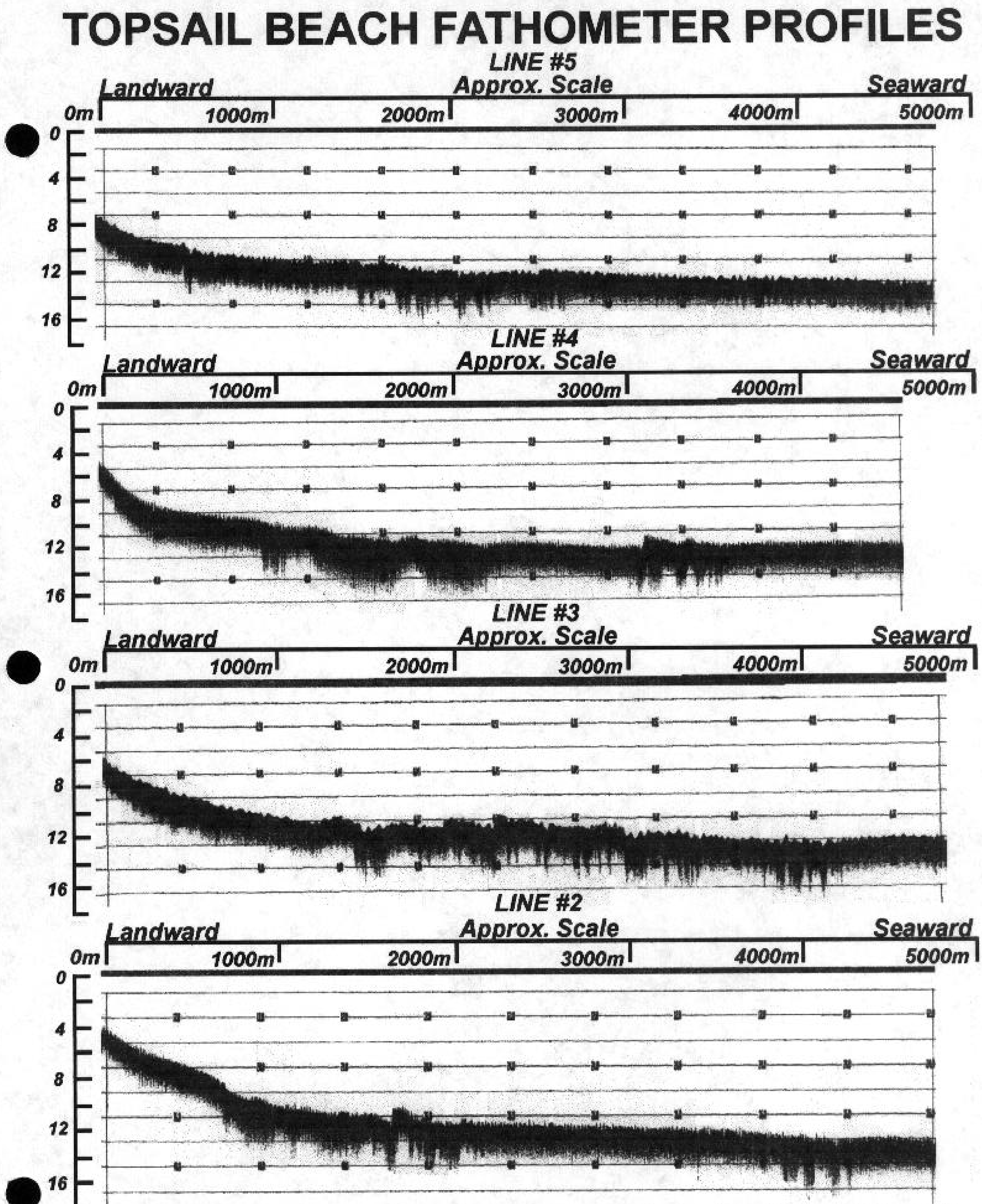
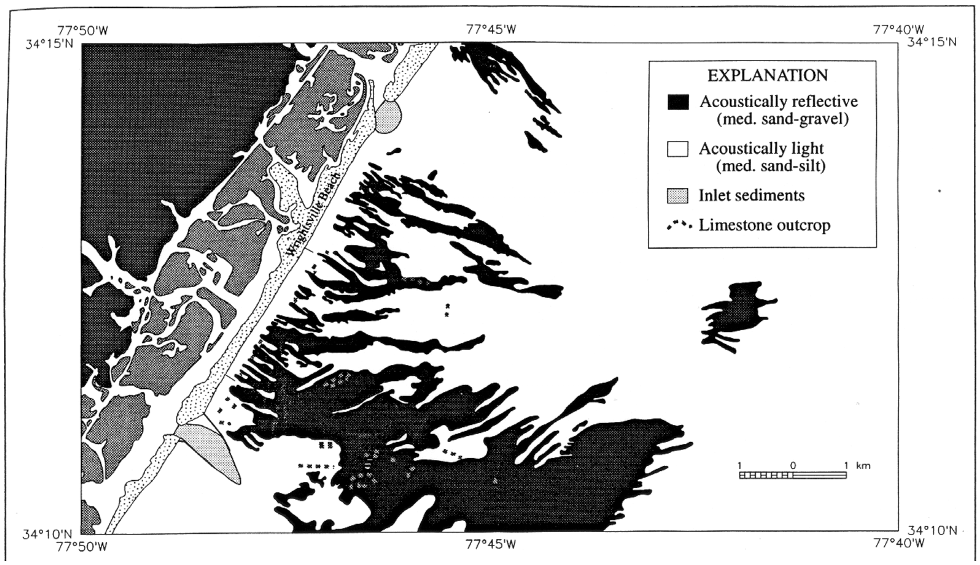


Figure 14. Fathometer profiles off Topsail Beach. Much of the area is blanketed by a thin layer of silty quartz sand. Hardbottoms are generally low relief.

Figure E-15: Facies Map Based of Wrightsville Beach based on Interpreted Sidescan Sonar Mosaic, Cores and Driver observations



Facies map based on interpreted sidescan sonar mosaic, cores and diver observations. Areas imaged as acoustically reflective on sidescan sonar mosaic are coarse sediments. The upper shoreface is characterized by a zone of rippled scour depressions (after Thieler et al, 1995)

Figure E-16: Illustration of Overlapping Shore-parallel Sidescan Sonar Images

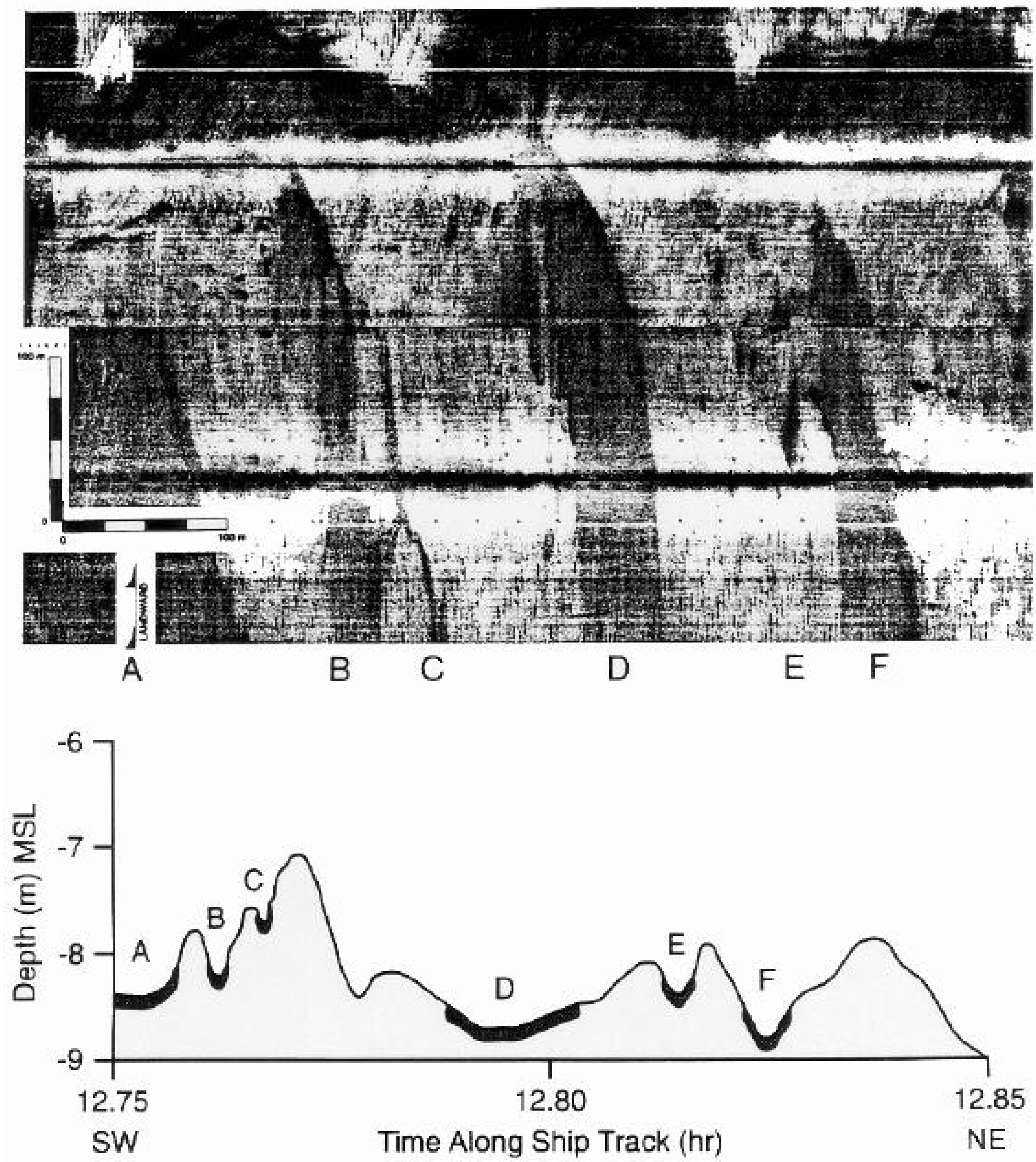
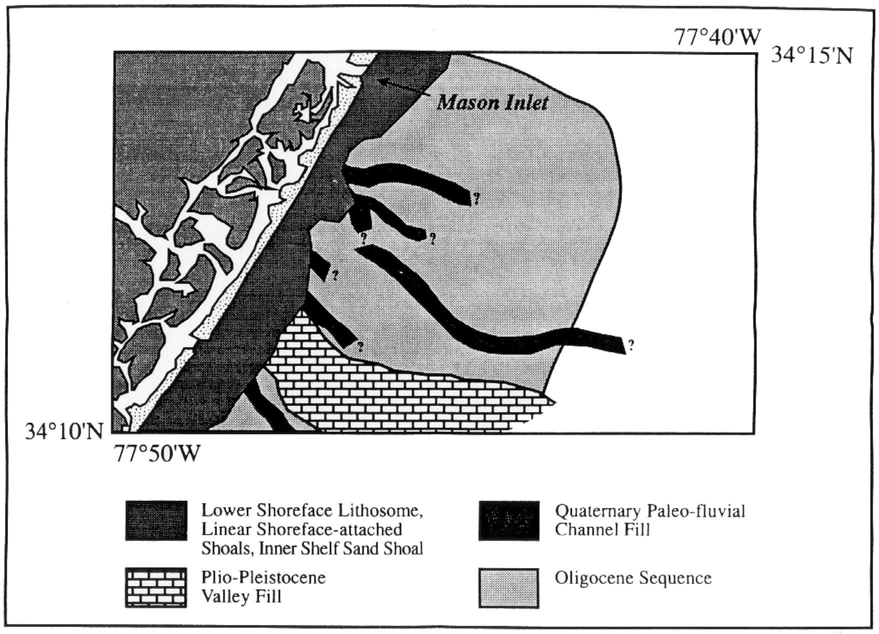


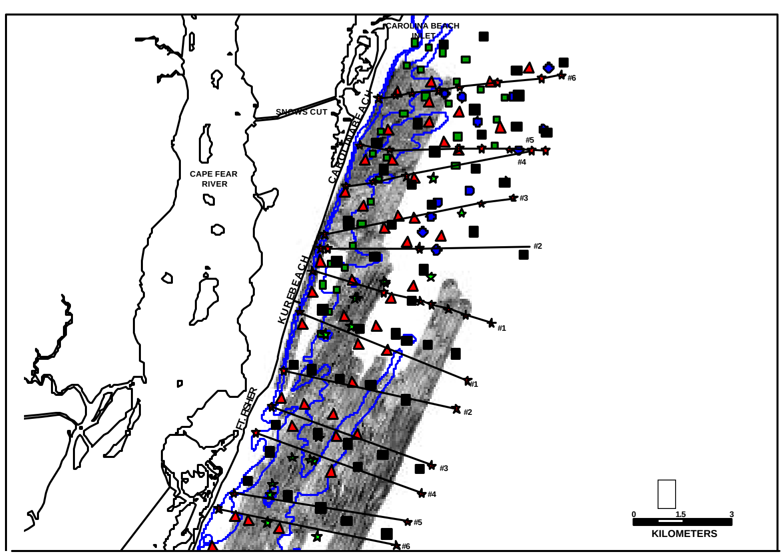
Illustration showing overlapping shore-parallel sidescan sonar images depicting rippled scour depressions (A-F) that lie immediately seaward of the surf zone. Coarse sediments are imaged as dark colored regions on the sidescan swaths and are contained within the topographic lows. Lighter areas are fine sands. Irregular dark patches within the lighter colored areas represent hardbottoms. Depressions are generally shallow with maximum relief of less than 1.0m. Most of the trough-like areas extend to the base of the shore =face (after Thieler et as, 1995).

Figure E-17: Geologic Map of Shoreface off Wrightsville Beach



Geologic map of the shoreface off Wrightsville Beach. An Oligocene siltstone sequence underlies much of thee area. Pilo-Pleistocene limestones form the valley-fill sequence along the southern section of the area. Hardbottoms are generally low relief with scarps less than 0,50m high (after Snyder et al, 1994; Thieler et al, 1995).

Figure E-18: Bathymetry off Carolina and Kure Beaches



Map depicts the bathymetry, locations of fathometer profiles, cores and sidescan sonar mosaics. Note the complexity of the shoreface bathymetry off this headland area.

Figure E-19: Fathometer Profiles off of Carolina Beach

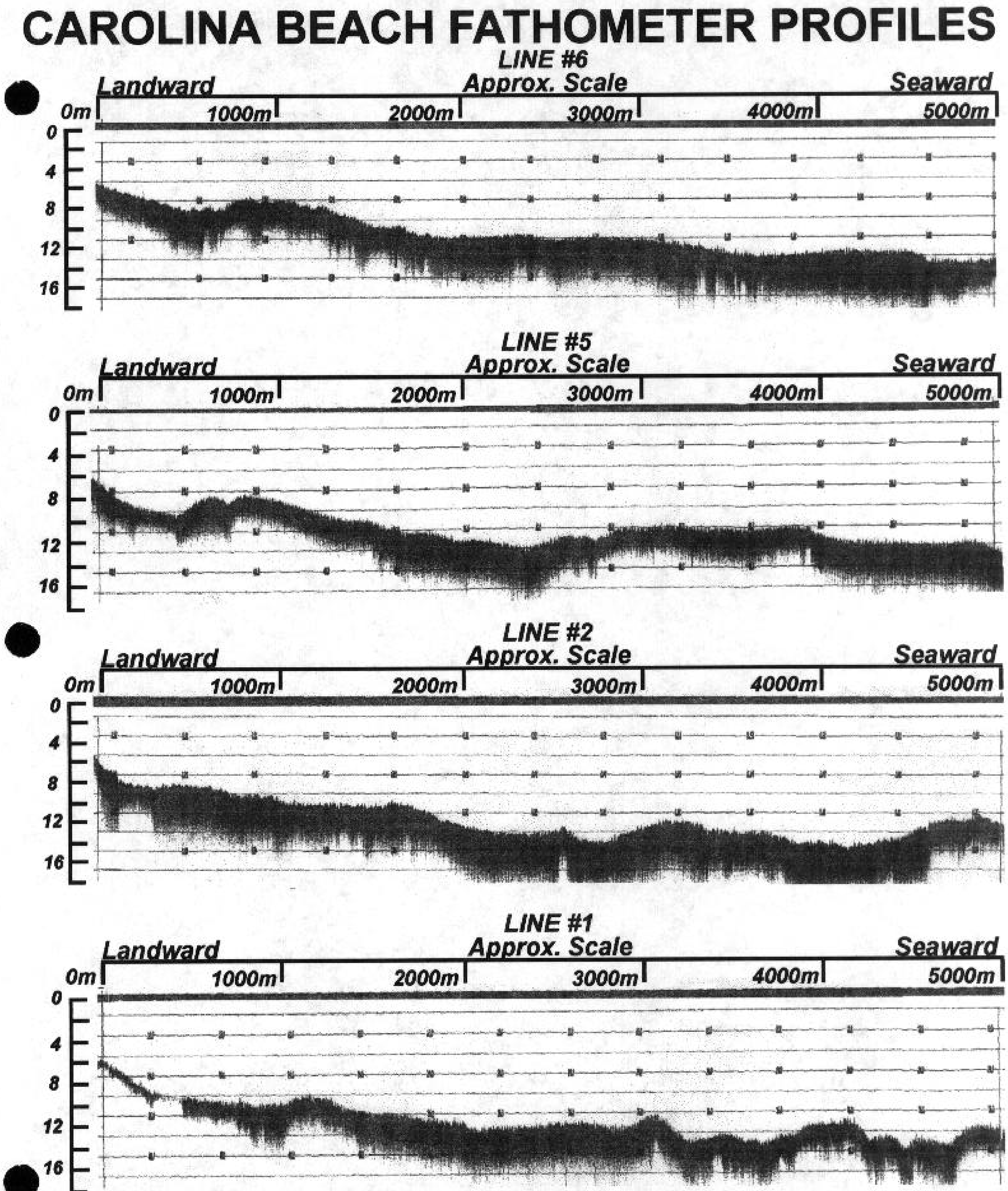


Figure 19. Fathometer profiles off Carolina Beach. Broad bathymetric highs are related to the presence of shore attached ridges and extensive hardbottoms.

Figure E-20: Fathometer Profiles off Kure Beach (North)

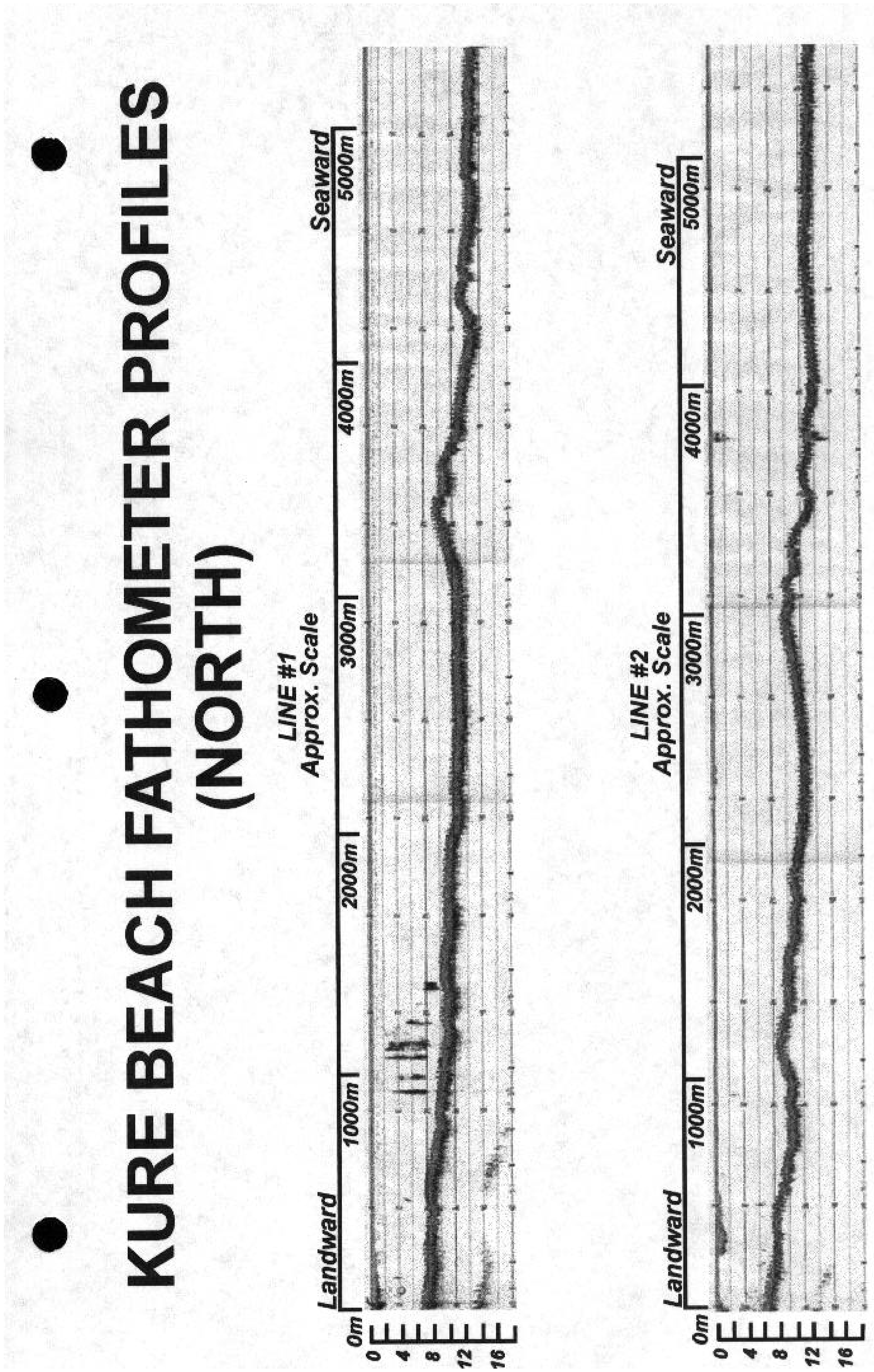


Figure 20. Fathometer profiles off Kure Beach. The profiles depict the irregular nature of the shoreface off the headland.

Figure E-21: Fathometer Profiles off Kure Beach (South)

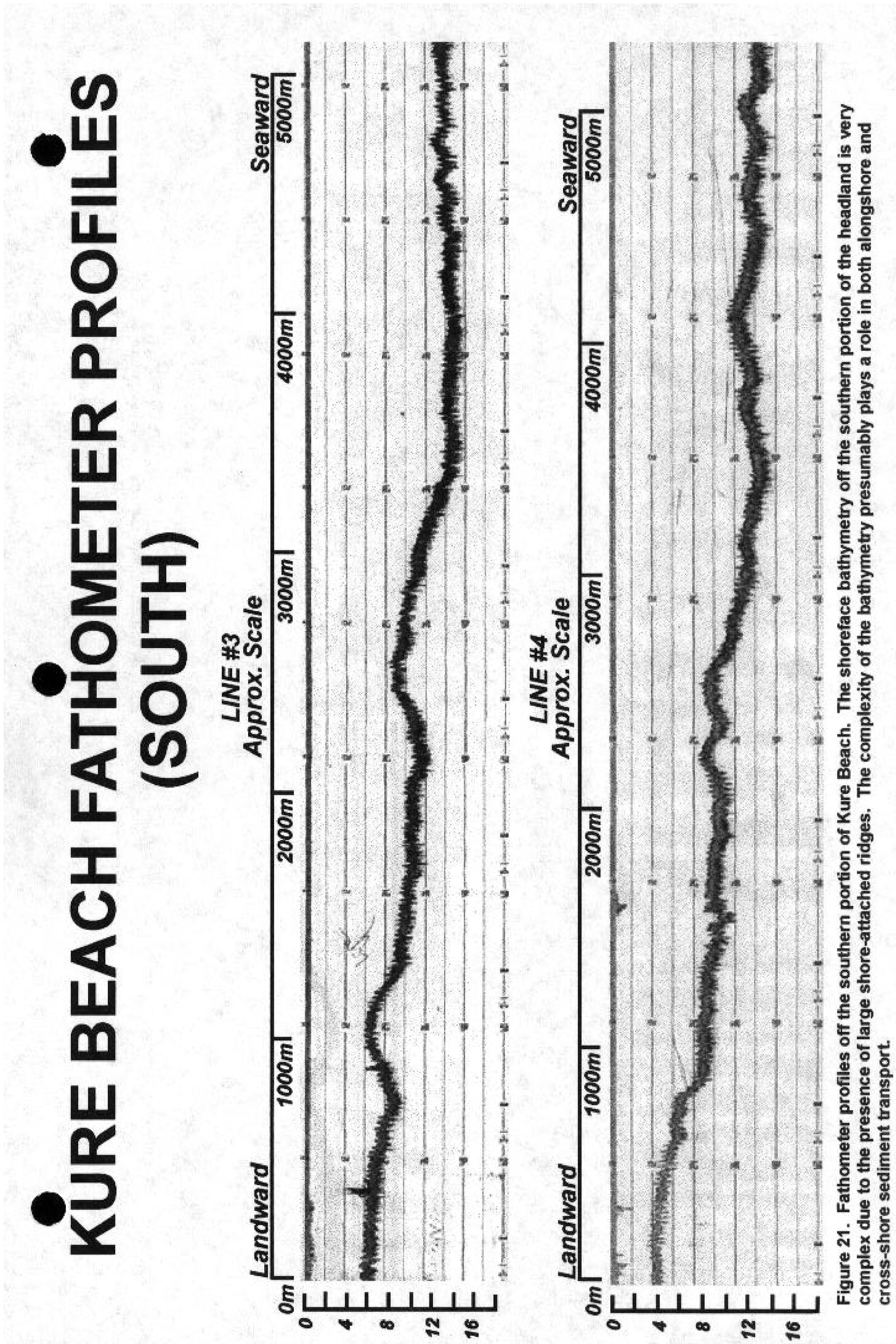
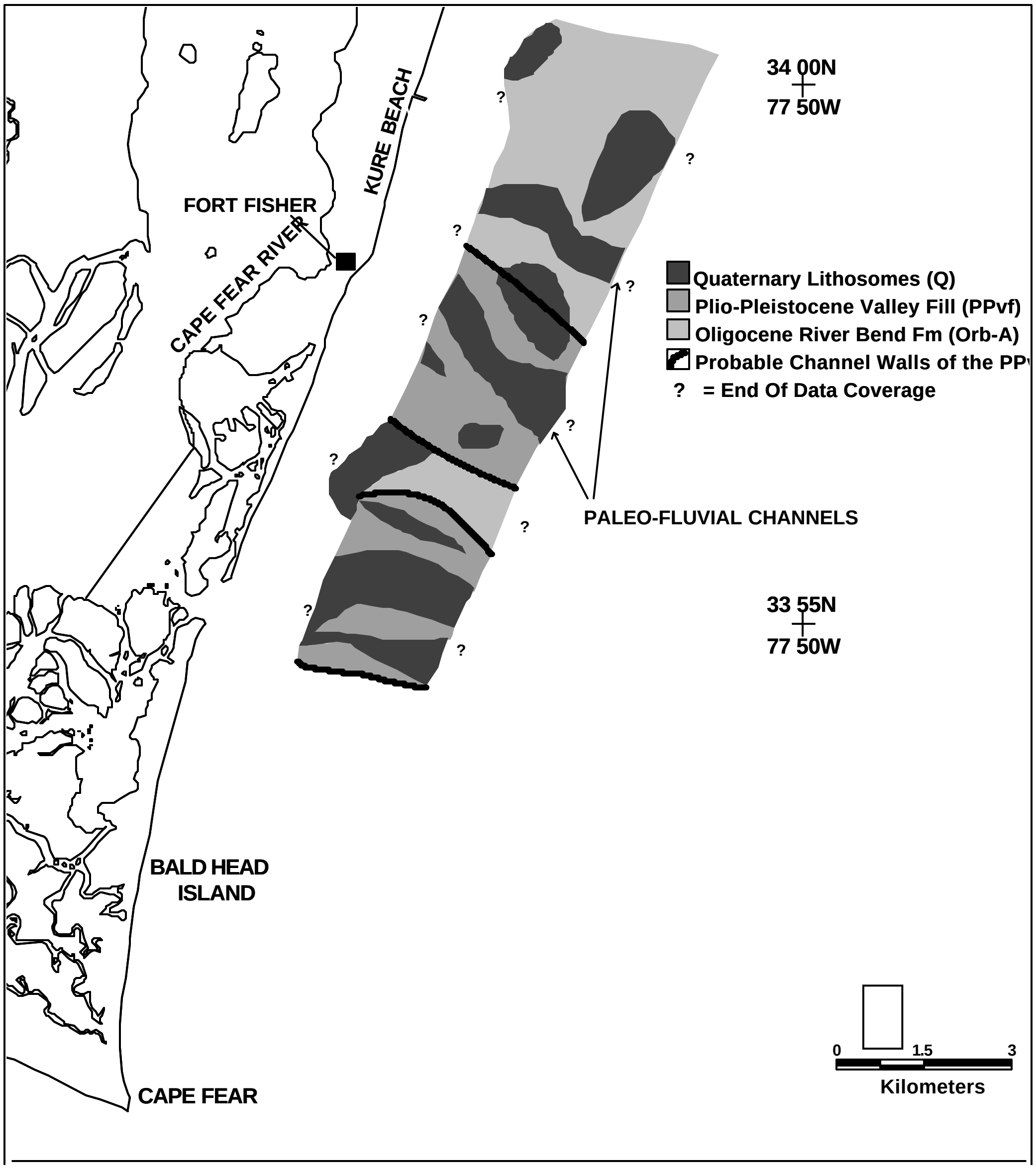


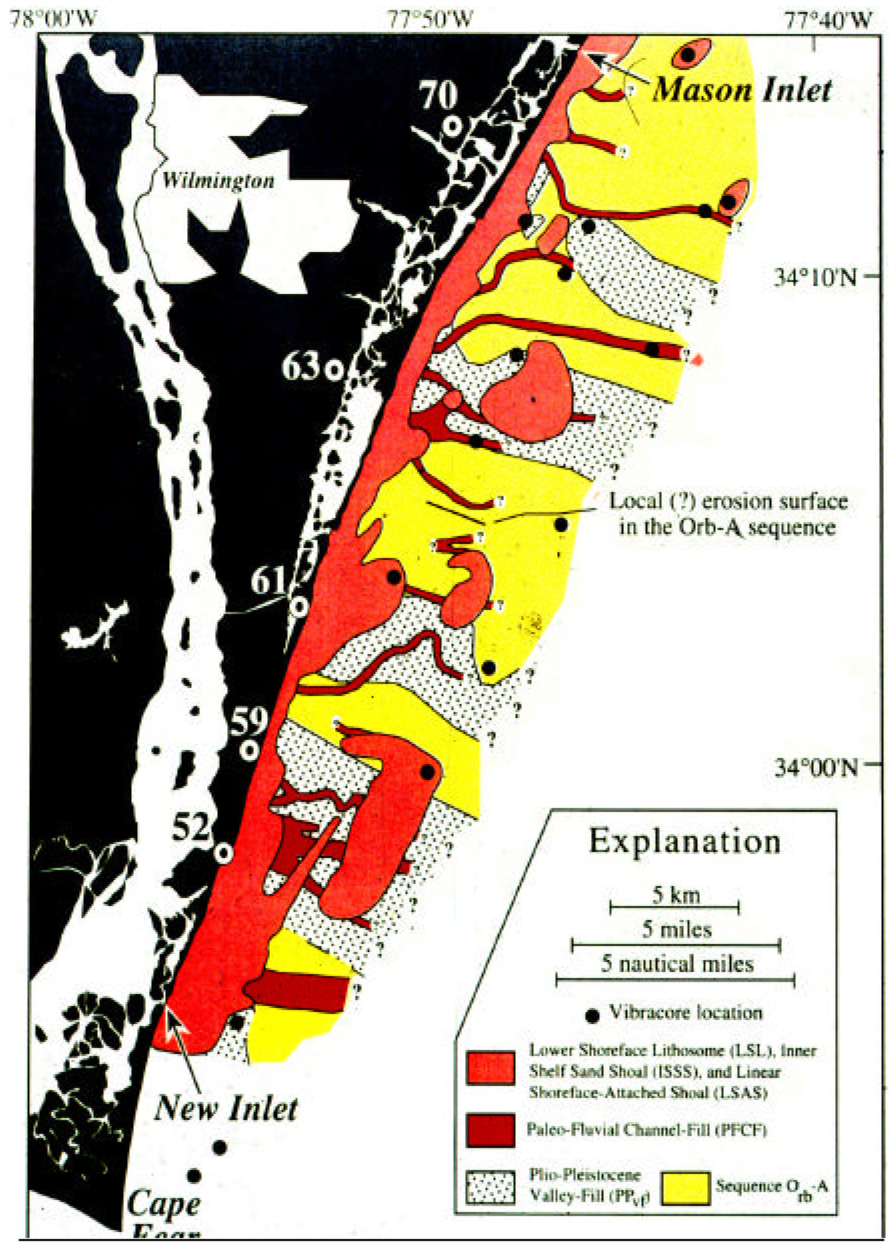
Figure 21. Fathometer profiles off the southern portion of Kure Beach. The shoreface bathymetry off the southern portion of the headland is very complex due to the presence of large shore-attached ridges. The complexity of the bathymetry presumably plays a role in both alongshore and cross-shore sediment transport.

Figure E-22: Near Surface Map of Kure Beach Shoreface



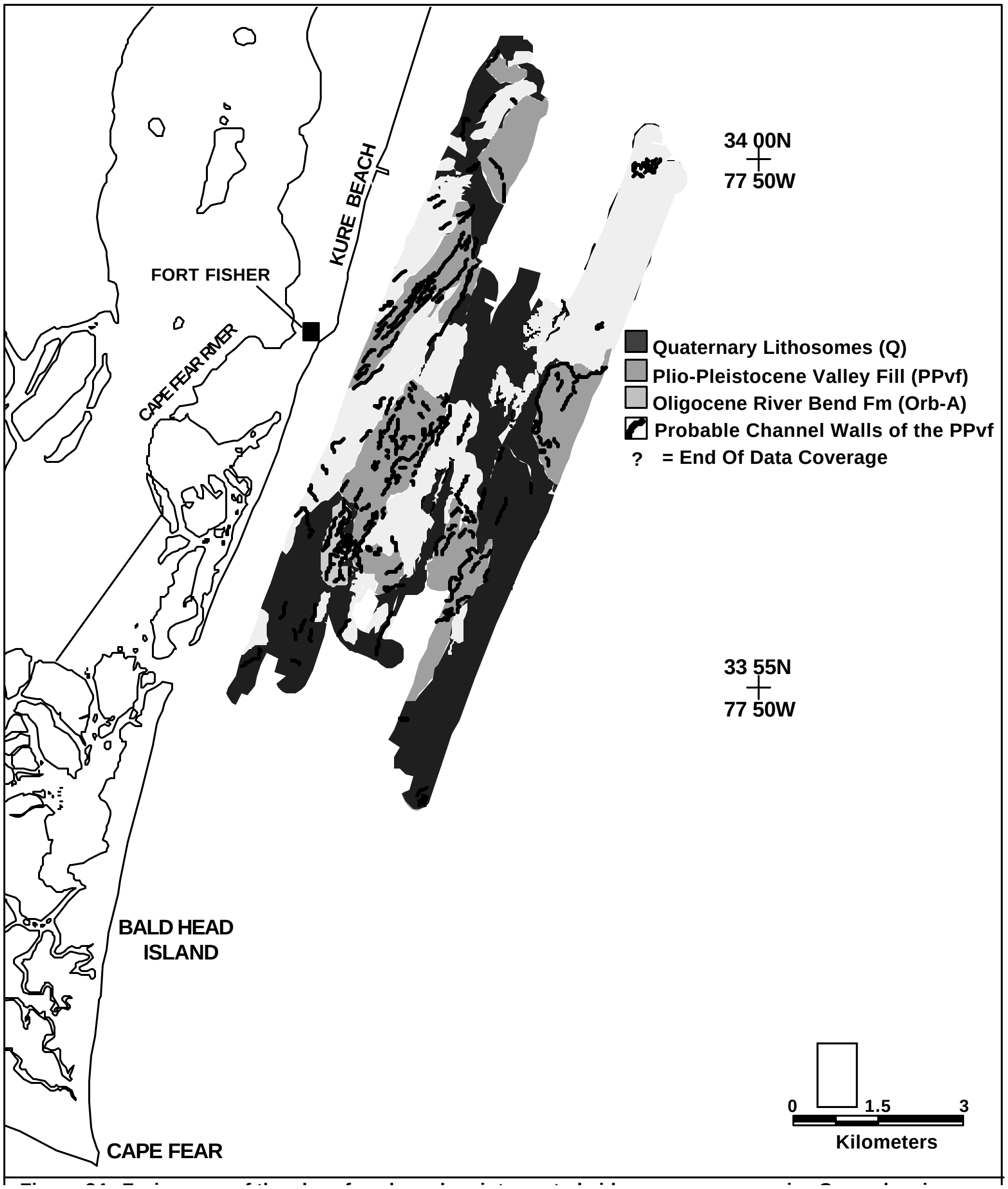
Near surface geologic map of the middle and lower shoreface off Kure Beach (after Marcy, 1997). Map is based on a network of high-resolution seismic reflection profiles. The northern most paleo-channel was recently excavated for excellent quality beachfill material for Kure Beach. Channels are incised into the Tertiary units and are often overlain by late Pleistocene sequences (coquina).

Figure E-23: Near Surface Geologic Map of the Shoreface off SE North Carolina



Geologic map of the shoreface. Oligocene and Plio-Pleistocene units are exposed across much of the shoreface. Major Pleistocene channels deposits are located offshore of the headland segment of Carolina and Kure Beaches (after Snyder et al, 1994)

Figure E-24: Facies Map of Southern Portion of Kure Beach Shoreface



Facies map of the shoreface based on interpreted sidescan sonar mosaic. Several major categories o bottom types are depicted. Hardbottoms with low relief (less than 0.5m) dominate the shoreface off Kure Beach. Northeast/southwest trending scarps off the nearshore area of Kure Beach are related to the outcrop pattern of the Oligocene River Bend Formation (after Marcy, 1997).

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William J. Cleary

22 April 1999

LIST OF PLATES

Plates

Plate E-1:

Plate 1. Oblique aerial photographs of North Topsail Beach. A.) North view (December 1974) showing position of old road, scarped dunefield, vegetated washover terraces. Note lack of development. Shoreline protuberance at north end of island is due to the presence of New River Inlet. B.) North view of northern portion of North Topsail Beach (November 1995). The road pictured at "A" was relocated in the early 1990's. Portions of the old roadbed are visible in some areas (arrow). Note lack of dunes and scarped grasslands along much of this section of the barrier.

Plate E-2:

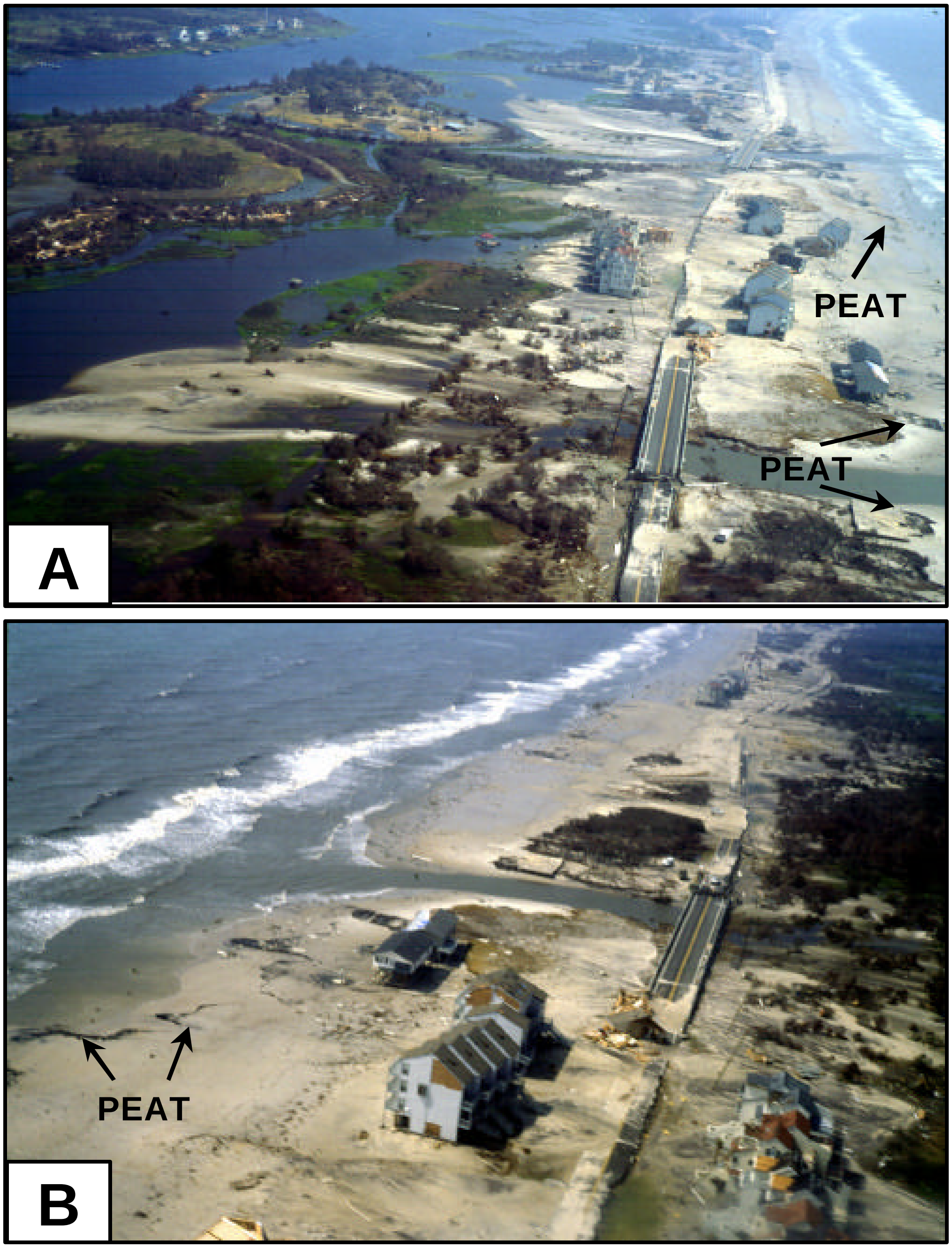

Plate 2. Post-Hurricane Fran views of North Topsail Beach (September 6, 1996). A.) North view illustrating extensive washover fans and terrace and breached portions of barrier. Dark areas on beach are outcrops of peat and stump forest that underlie portions of the old roadbed. Compare to Plate 1B. Townhouses are referenced in Plate 1B. B.) South view of same area pictured in "A", overwash penetration extended across the entire barrier and well into the marsh and lagoon. Note extensive peat deposits on intertidal beach that testify to the lack of sand in the modern coastal system.

Plate E-3:

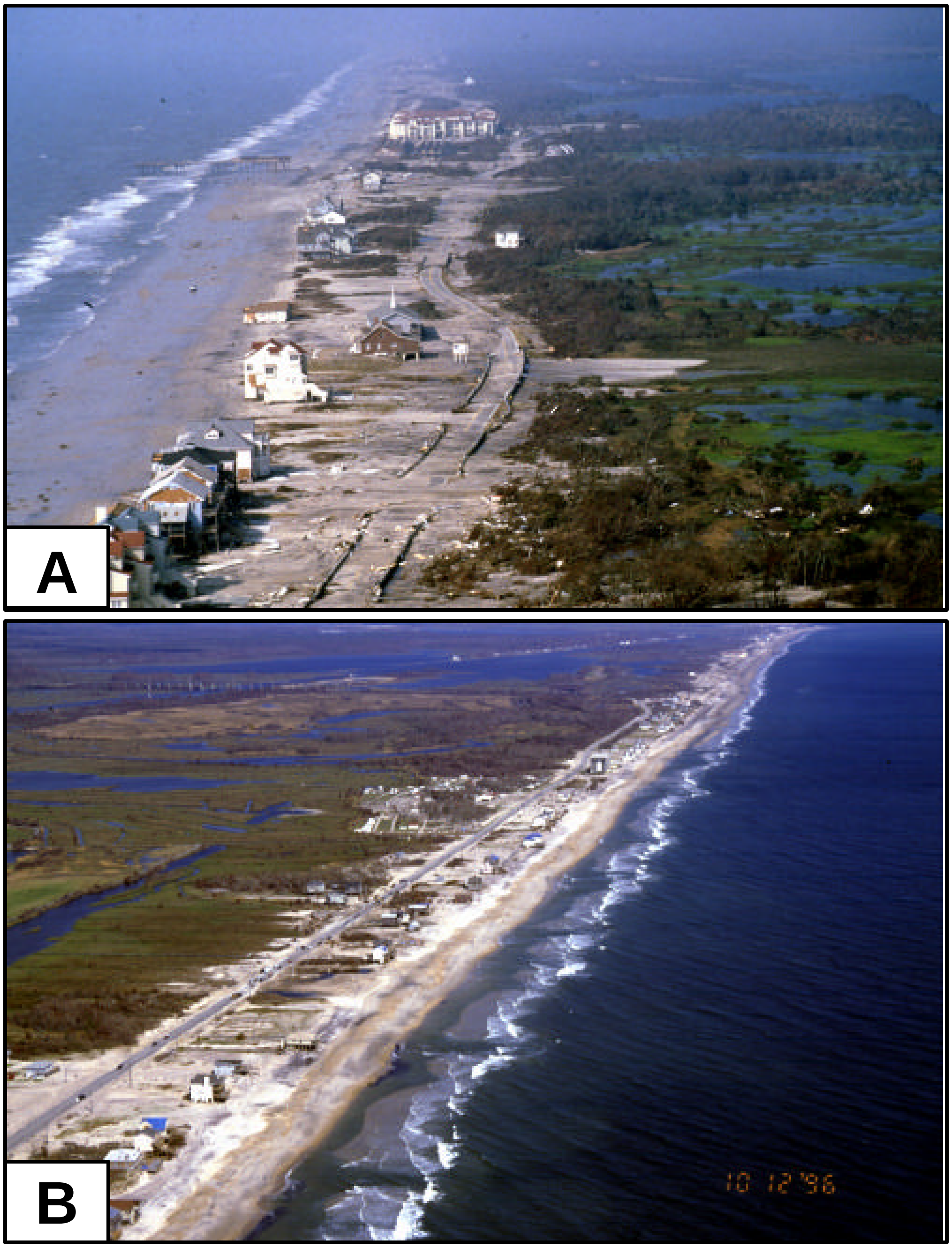

Plate 3. Oblique aerial photographs of the southern portion of North Topsail Beach after Hurricane Fran (September 6,1996). A.) South view of extensive washover terraces, note only scattered segments of grasslands remain. Most topographic lows were infilled with washover materials. B.) North view from region just south of high rise bridge. Washover terraces extend across entire island in most regions. Note scattered outcrops of peat.

Plate E-4:

Plate 4. Landward view of Surf City (12/75) showing vegetated flood tidal delta and the extensive development along the low lying finger canals. Note the nature of the dune line and dune field.

Plate E-5:

Plate 5. Post Hurricane Fran views of Surf City (10/12/96). A.) Seaward view of low area fronting old tidal delta and extensive washover terraces. A number of structures were destroyed along the shoreline segment in the center of the photograph. B.) Landward view of the same area in "A", 0.5 to 1.0m of washover sediment covered the roadbed along much of this section of the town. Note the structural damage along this section of the beach.

Plate E-6:

Plate 6. Post Hurricane views of Topsail Beach. A.) Sea Vista Hotel along the southern portion of the area is surrounded by an extensive washover terrace that extended beyond the third row of homes (9/7/96). B.) Seaward view of the same area in "A" (10/12/96). Sand has been scraped into a low dune-like feature along most of the southern end of the area. Note the extensive washover terraces developed in this area.

Plate E-7:

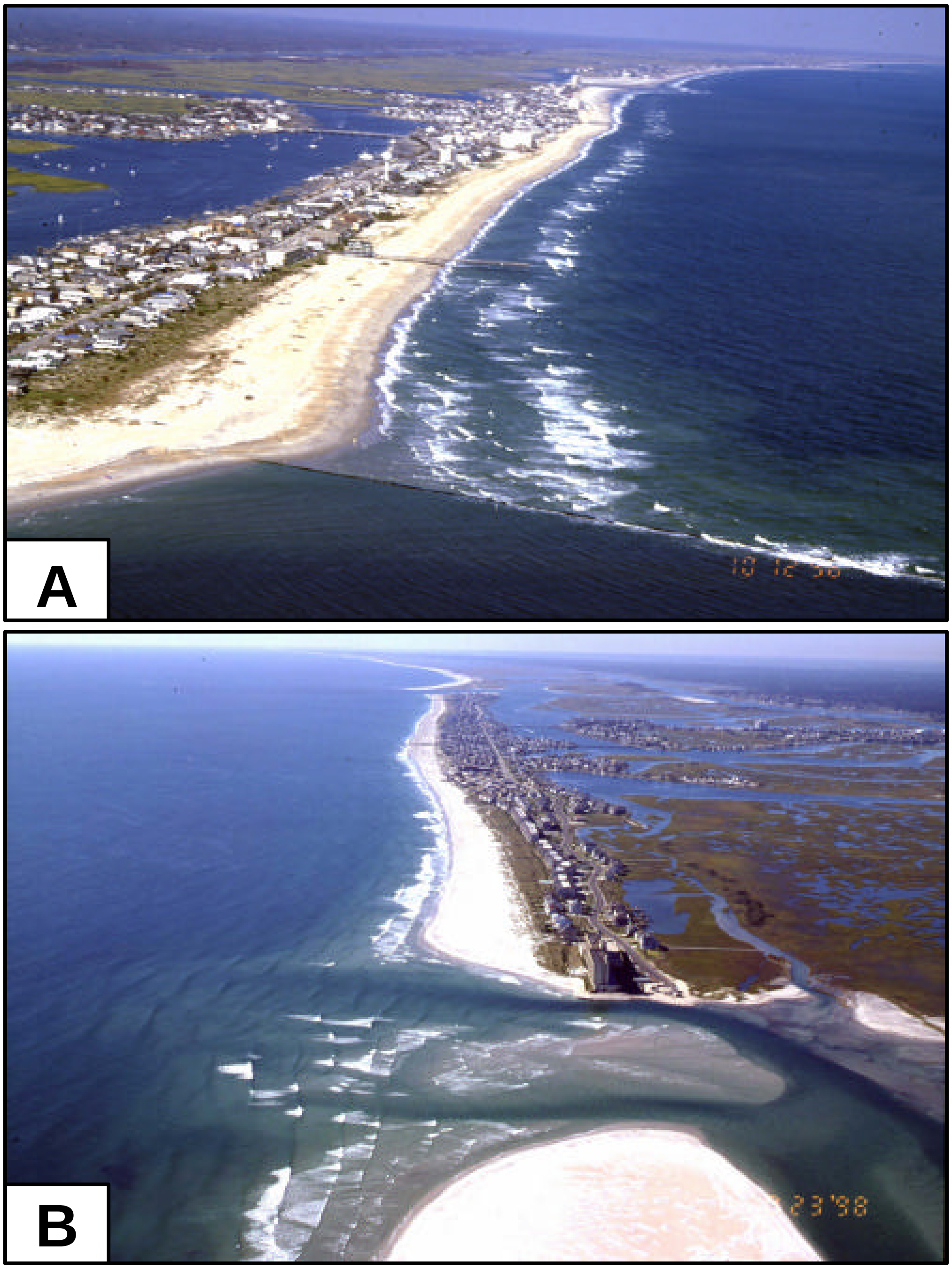

Plate 7. Views of Wrightsville Beach. A.) North view (10/12/96) showing fillet developed in the lee of the jetty and the shoreline protuberance along the mid-barrier section. B.) South view of the island (9/23/98) illustrating the shoreline bump in the vicinity of Moore's inlet (now closed) and the offset in the building line along this section of the shoreline. Mason's Inlet forms the northern border of the barrier. Sand bags line the downdrift shoulder along the Shell Island Resort in an effort to protect theresort from the rapidly migrating inlet. Note the accretion zone along the oceanfront south of the inlet.

Plate E-8:

Plate 8. South view of Wrightsville Beach after Hurricane Bonnie (8/26/98) and the bump in the shoreline along the mid-barrier section. Note the variations in position of the homes and large multi-unit dwellings along the beach. Most of the chronic erosion and structural damage that is associated with storm events is restricted to this high hazard zone.

Plate E-9:

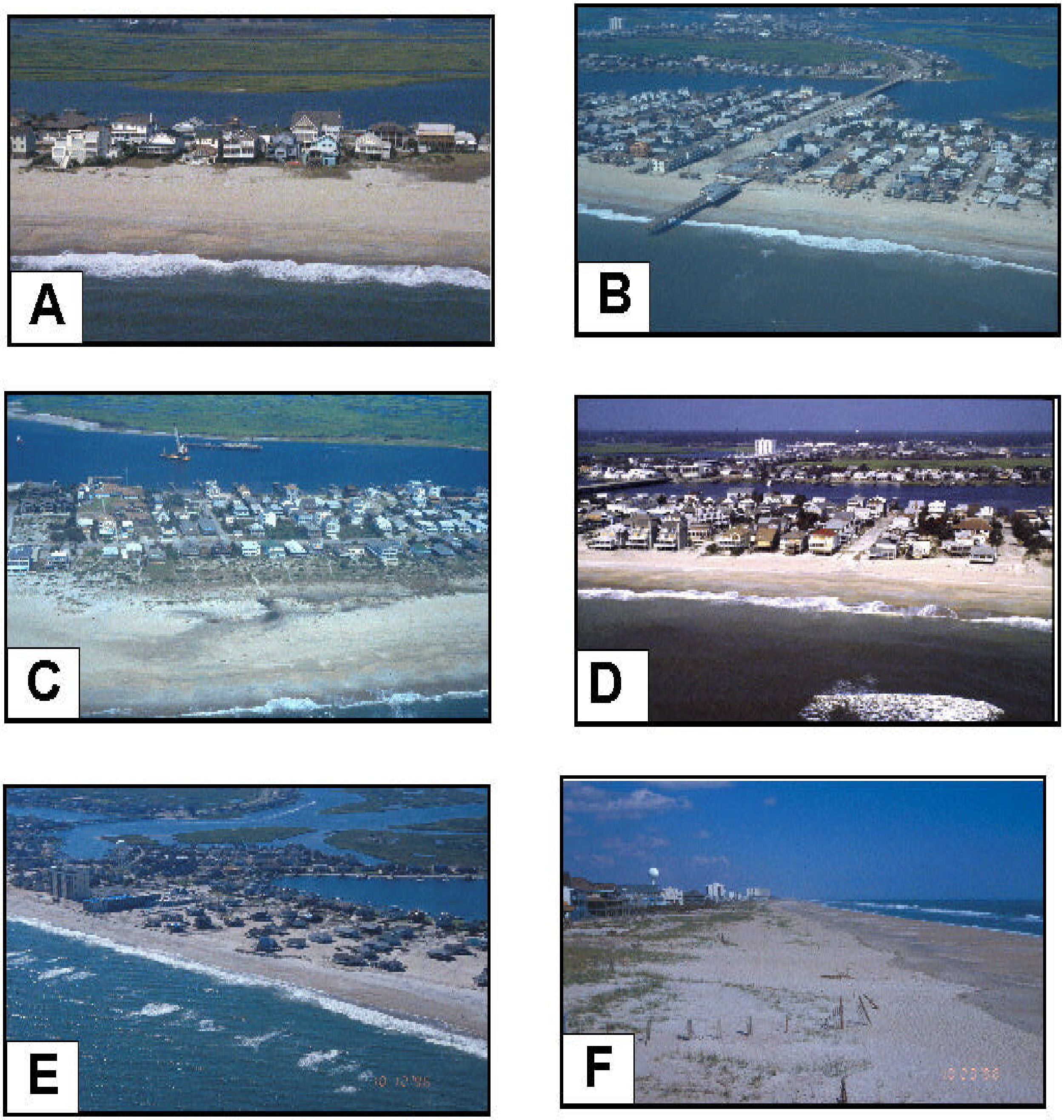

Plate 9. Post storm views of Wrightsville Beach. A.) Landward view of south central portion of beach. Little structural damage occurred in this area. Localized overwash is evident. B.) Landward view of shoreline in vicinity of Mercer's Pier. Shoreline north of the pier was susceptible to overwash and minor structural damage was reported in the area. C.) Landward view of prograded shoreline segment near jetty. Little damage was reported in this area due to the wide and high dune field. Localized dune erosion and overwash is evident. D.) Landward view of shoreline south of Mercer's Pier. Minor overwash and minimal damage occurred along this section. E.) Landward view of shoreline in the vicinity of Old Moore's Inlet. The shoreline in this vicinity was the site of the worst structural damage and erosion on Wrightsville Beach due to the poor condition of the beach along the "shoreline bulge". F.) North view of artificial dune/beach almost two months after Hurricane Fran impacted the area. Much of the dune remained in place. Minor washover features are seen along the intact dune.

Plate E-10:

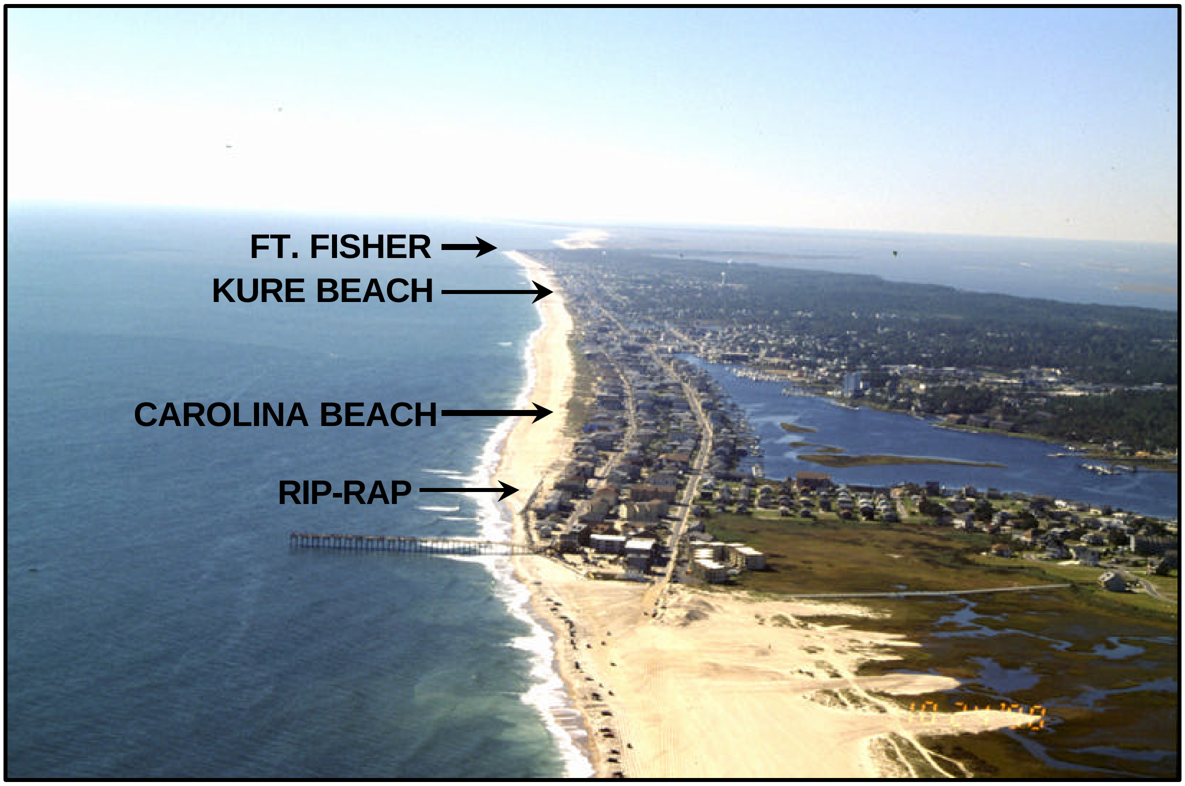

Plate10. South view of Carolina Beach and local environments (10/24/98). Note the lagoon narrows and terminates at the headland portion of Carolina Beach. The chronic erosion and overwash susceptible zone is located at the bottom of the photo. The shoreline stretch south of the pier was most heavily impacted by the hurricanes of 1996. Remnants of the washover features are still visible two years later.

Plate E-11:

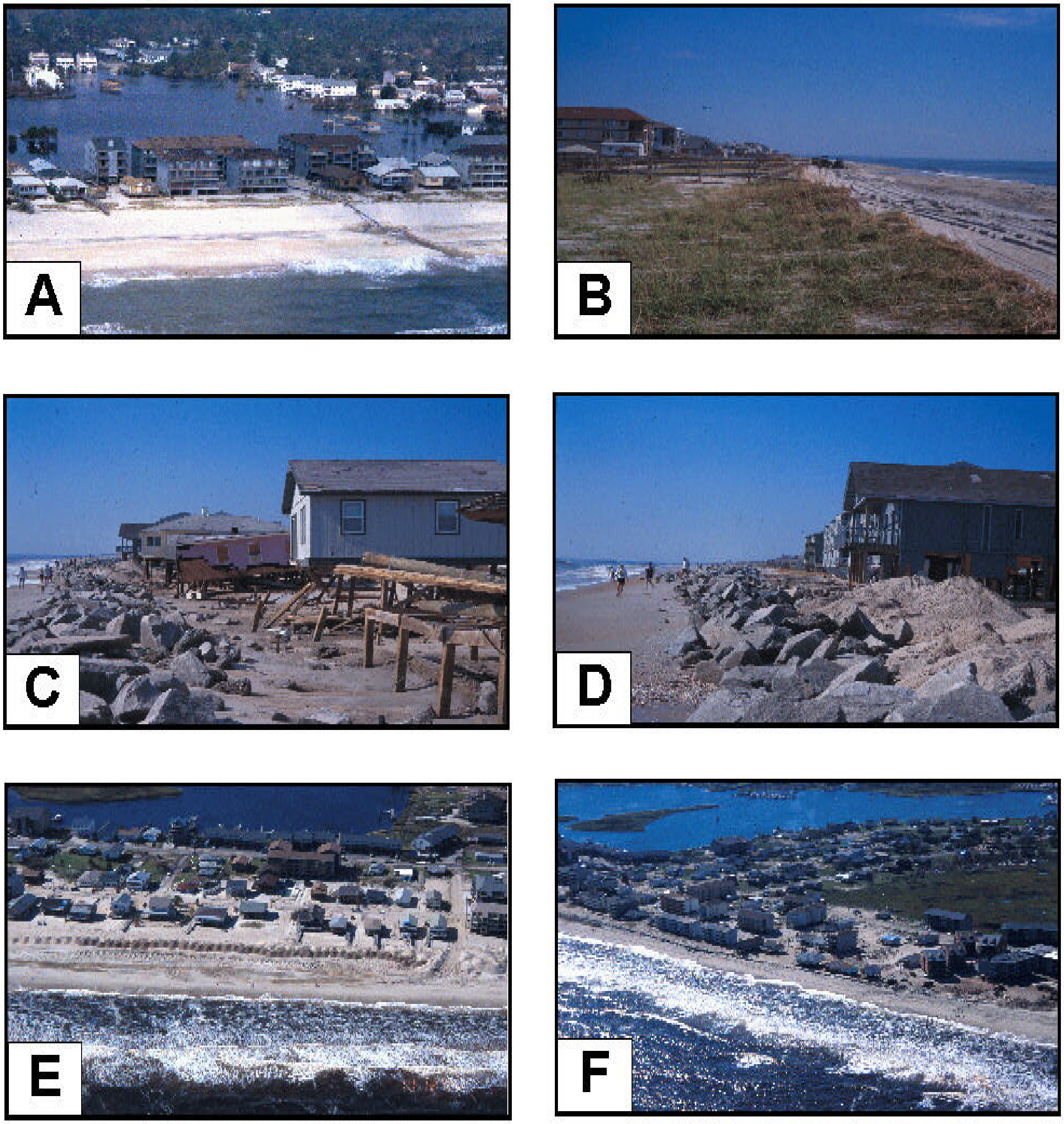

Plate11. Post storm views of Carolina Beach. A.) View of Carolina Lake showing eroded dune and flooding of the low -lying area that was once an inlet/lagoon system. B.) North view of eroded artificial dune near the north end of Carolina Beach. Overwash extended across the dune in several places. Damage was minimal. Bulldozing of the profile was common. C.) South view of structural damage near rip-rap at north end of Carolina Beach. D.) Structural damage south of rip-rap was minimal. Overwash extended across the dune and rocks in this area. E.) Air view (10/12/96) one month after Hurricane Fran struck the area. Washover materials were scraped from the roads and placed along the berm/dune system. This area was the site of extensive washover fans. F.) South view of area depicted in "E". Areas not protected by the dune/berm system were overwashed and prone to structural damage.

Plate E-12:

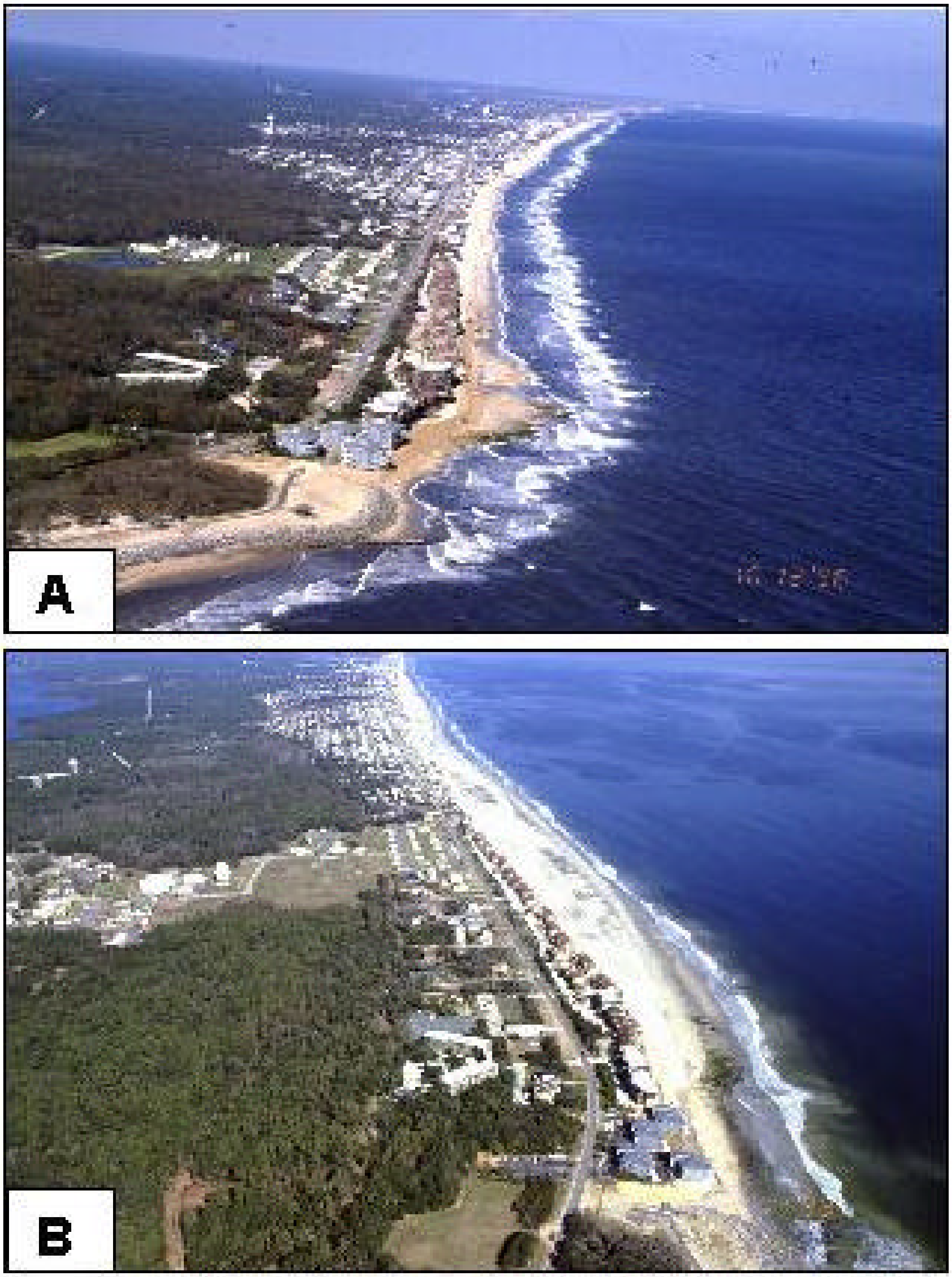

Plate 12. North views of the Carolina Beach/Kure Beach subaerial headland shoreline segment. A.) View (10/12/96) from the seawall at Fort fisher shows the narrow beach and the coquina outcropping along the southern section of the area. The erosion resistant calcarenite forms a small protuberance in the shoreline. B.) North view (1/11/98) from the terminus of the seawall at Fort Fisher showing the replenishment project at Kure Beach. Coquina outcrop[is visible at the bottom of the photograph. Beachfill was derived from ancestral channels of the Caer Fear river several miles offshore.

Plate E-13:

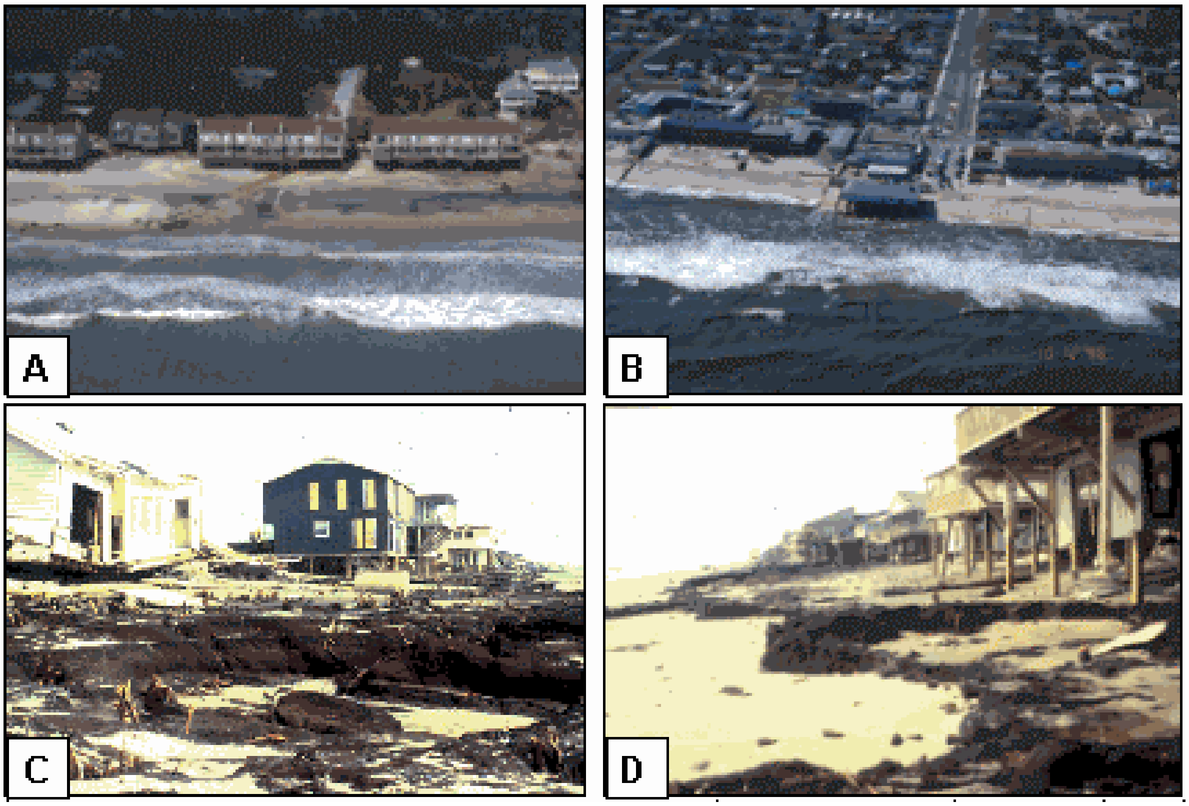

Plate 13. View of damage and beach erosion following Hurricane Fran (9/6/96). Photographs C and D by Robert Young. Southern portion of Kure Beach (9/6/96). Perched beach was eroded exposing underlying humate sandstone and Pleistocene stump forest. B.) Groin field and pier at Kure Beach (10/12/96). Minor damage occurred along this stretch of shoreline and for the most part damage was confined to the oceanfront row. Overwash extended across the road. C.) South view of the outcrop of the humate sand and stumps. Modern beach was very thin along much of this area. D.) Northern extension of sandstone unit contains less stumps. Remnants of this unit can also be found in the nearshore area.

Plate E-14:

Plate 14. Views of replenishment project at Kure Beach. A.) South view (1/11/98) of project and terminus just north of Forth Fisher. Shoreline offset toward top of photo is related to the contrasting nature of the underlying materials. Sheephead Rock is located offshore in upper left corner. B.) Landward view (1/11/98) of northern portion of the replenishment project at Kure Beach and the remainder of the headland segment. Carolina Beach Inlet is seen in the upper right of the view.

APPENDIX F
POST STORM DAMAGE SURVEY

Residential Structures

Identification Information

- Address ____
- Telephone Number: ____________________________________
- Is structure primary or secondary residence? ___________________
- Is the structure (pick one)
  - _____Oceanfront
  - _____1st row behind oceanfront
  - _____Ocean Block
  - _____Sound or Back Bay
  - _____Other, explain: ________________________

Construction Information

- Foundation type (pick one)
  - ______Slab
  - ______Piling
  - ______Concrete Block
  - ______ Other, explain: _________________________
- First floor elevation:_______________________________________
- Age of structure (pick one)
  - ______0-10 years
  - ______11-20 years
  - ______21+ years

Damage Information

- How long was the structure inundated? _________________________
- Did you evacuate? ____
- If yes, how long were you displaced? __________________________
- What was the damage mechanism? (pick one)
  - ______ Surge
  - _______Inundation
  - _______Erosion
  - _______Wind
  - _______Other, explain: ____________________________
- Depreciated replacement cost of structure: $_______________________
- How much damage was done to the structure? (pick one)
  - ______0-25%
  - ______26-50%
  - ______51-75%
  - ______76-100%

Please provide a brief description of the structural damage sustained:

Please provide a brief description of the personal property damage sustained (structure contents, vehicles etc.)

Please provide a brief description of utility damage or interruption (water, electric etc):

What was the land or lot damage? ___________________________________

How many square feet? _____________________________________

Value (dollar damage values are on FIA claims)? _______________

Is the land re-buildable? _____________________________________

Commercial Structures

Identification Information

- Name of Business:______________________________________
- Type of Business:_______________________________________
- Name and position of interviewee:_________________________
- Number of Employees:___________________________________
- Address: ____
- Telephone Number: ______________________________________
- Normal operating season:__________________________________
- What is the location of the structure (pick one)
  - _____Oceanfront
  - _____1st row behind O/F
  - ______Ocean Block
  - ______Sound or Back Bay
  - ______Other, explain: __________________________

Construction Information

- Foundation type (pick one)
  - ______Slab
  - ______Piling
  - ______Concrete Block
  - ______ Other, explain: _________________________
- First floor elevation:____________________________
- Age of structure (pick one)
  - ______0-10 years
  - ______11-20 years
  - ______21+ years

Damage Information

- How long was the structure inundated? _________________________
- Did you evacuate? ____
- If yes, for how long was the business closed? ____________________
- How much income did you lose due to the event? ________________
- What was the damage mechanism? (pick one)
  - ______ Surge
  - _______Inundation
  - _______Erosion
  - _______Wind
  - _______Other, explain: _______________________
- Depreciated replacement cost of structure: $_______________________
- How much damage was done to the structure? (pick one)
  - ______0-25%
  - ______26-50%
  - ______51-75%
  - ______76-100%

Please provide a brief description of the structural damage sustained:

Please provide a brief description of the inventory and equipment that was damaged:

Please provide a brief description of the personal property damage sustained (personal effects, personal vehicles etc.)

Please provide a brief description of utility damage or interruption (water, electric etc):

What was the land or lot damage? ________________________________

How many square feet? ___________________________________

Value (dollar damage values are on FIA claims)? _______________

Is the land re-buildable? __________________________________

Public Infrastructure

Describe any damage that was incurred at public or municipal buildings:

Describe any infrastructure damage (dune crossovers, streets, sewers, seawalls, etc). Include the damage mechanism (surge, wave, inundation, etc) and the magnitude in feet or square feet, etc.

General Information

Please list all state, local and private entities that provided assistance. Give a point of contact and phone number, if possible.

Entity	POC	Phone number

Please describe the evacuation route for the affected area. Give road names, speed limits, and duration of evacuation activities.