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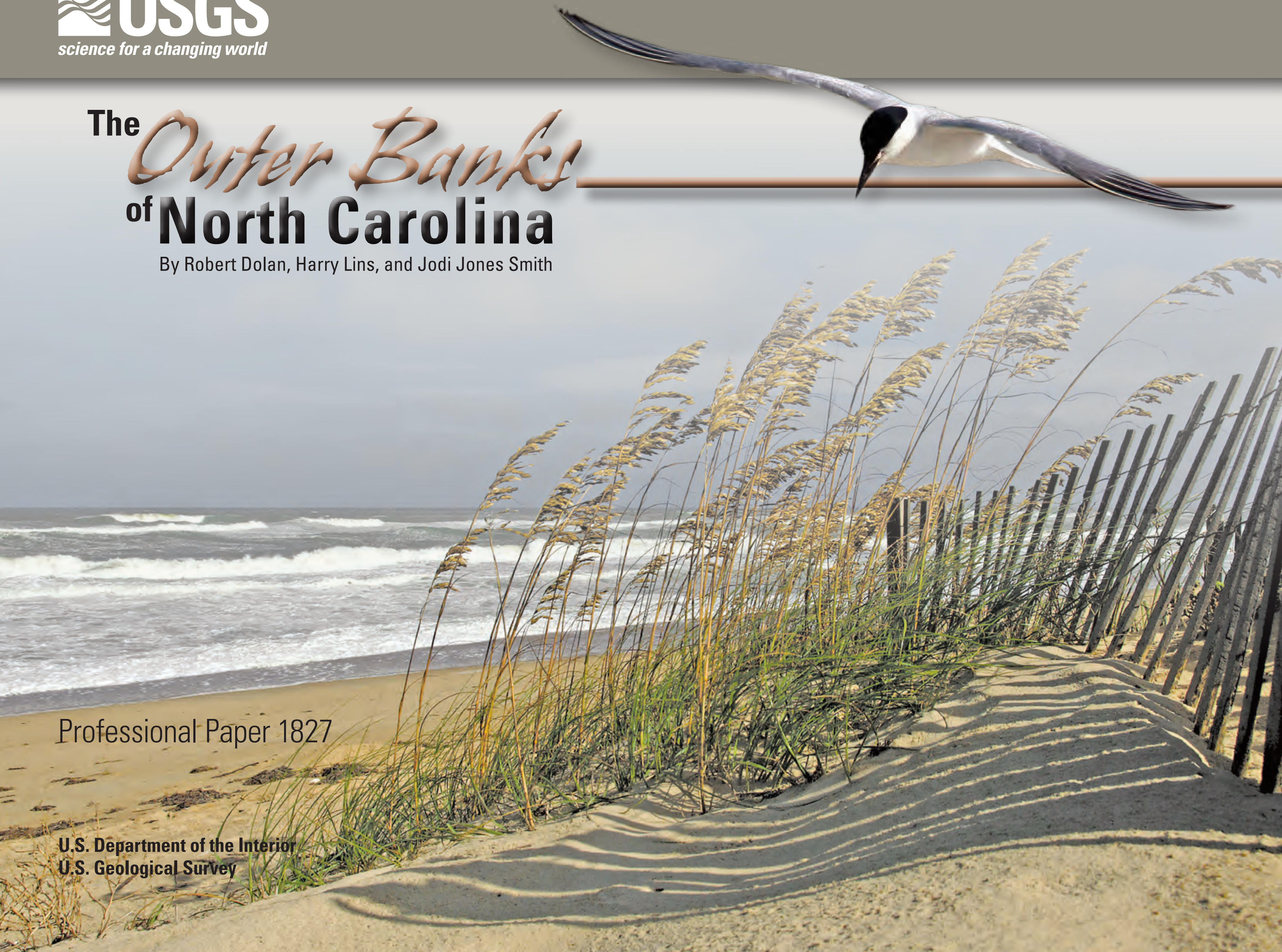
The Outer Banks of North Carolina

By Robert Dolan, Harry Lins, and Jodi Jones Smith



Professional Paper 1827

U.S. Department of the Interior
U.S. Geological Survey

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SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Director

U.S. Geological Survey, Reston, Virginia: 2016

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Foreword

The U.S. Geological Survey published the first edition of "The Outer Banks of North Carolina"[1] in 1986 as a companion to "Geographical Analysis of Fenwick Island, Maryland, a Middle Atlantic Coast Barrier Island."[2] These two reports, issued respectively as U.S. Geological Survey Professional Papers 1177–B and 1177–A, were produced to demonstrate and promote the application of Earth-science information to sound environmental planning. Since its original release, "The Outer Banks of North Carolina" has been through four printings and has become one of the U.S. Geological Survey's most popular books, particularly among those who vacation on the Outer Banks.

Although much of the information contained in the original report has a timeless quality from an historical geology perspective, much of the report describes very dynamic processes; changes in barrier island landscapes are common. Additionally, in the two decades after its initial release, human development of the Outer Banks expanded more than during the previous three centuries. As a result, many sections of the report were out of date and in need of revision.

This second edition of "The Outer Banks of North Carolina" is not simply a revised or updated version of the original; it is a rewritten book containing new and expanded sections, more-detailed illustrations, and current information on coastal science. This book collects into one volume sketches, diagrams, and historical photographs that richly illustrate the natural and cultural history of the Outer Banks. In addition to being a valuable source of scientific information on the natural history and dynamics of these unique barrier islands, as well as on the effects of human activities on them, this book will deepen the experience of everyone who visits the Outer Banks.

Finally, I was saddened to learn that two weeks after this book was approved for publication, the senior author, Robert Dolan, passed away. Bob was my major professor in my Ph.D. program at the University of Virginia; from him I gained a deep appreciation of the forces that shape the coast and the inherent majesty of our barrier islands. Although Bob had spent his professional career as a member of the faculty at the University of Virginia, he had been a collaborator, consultant, and friend to numerous researchers and managers at the U.S. Geological Survey for nearly 50 years. His passing is a loss for all of us who had the pleasure of working with him during those years.

Suzette M. Kimball

Director, U.S. Geological Survey

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[1]Dolan, Robert, and Lins, H.F., 1986, The Outer Banks of North Carolina: U.S. Geological Survey Professional Paper 1177–B, 47 p.

[2]Dolan, Robert, Lins, H.F., and Stewart, John, 1980, Geographical analysis of Fenwick Island, Maryland, a Middle Atlantic coast barrier island: U.S. Geological Survey Professional Paper 1177–A, 24 p.

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Thanks also go to Rob Thieler and Loren Wehmeyer, both of the U.S. Geological Survey, whose careful technical reviews significantly improved the quality of this report. We also acknowledge Jane Carlson's editorial assistance.

Finally, we extend our sincerest thanks and appreciation to Carol Quesenberry, graphic designer, whose layout brings to life the beauty, mystery, and many moods of the Outer Banks, and to Mary-Margaret Coates, whose keen eye and understanding of geology transformed this book into what we hope will be a pleasurable read for all who enjoy the Outer Banks experience.

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(In pocket) The Outer Banks of North Carolina

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (knot)
	Volume	
cubic meter (m^3)	1.308	cubic yard (yd^3)
	Flow rate	
meter per year (m/yr)	3.281	foot per year (ft/yr)
kilometer per hour (km/h)	0.6214	mile per hour (mph)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F – 32)/1.8

Vertical coordinates are referenced to the North American Vertical Datum of 1988 (NAVD88).

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations Used in This Report

cm	centimeter
ft	foot
ft/yr	feet per year
in.	inch
km	kilometer
km/h	kilometers per hour
knot	nautical miles per hour
lidar	light detection and ranging
m	meter
m^3	cubic meter
m/yr	meters per year
mi	mile
mph	miles per hour
yd^3	cubic yard
GPS	Geographic Positioning System

The Outer Banks of North Carolina

By Robert Dolan,[1] Harry Lins,[2] and Jodi Jones Smith[1]

Abstract

The Outer Banks of North Carolina are excellent examples of the nearly 300 barrier islands that rim the Atlantic and Gulf coasts of the United States. These low, sandy islands are among the most dynamic natural landscapes occupied by man. The physical interface between land and sea is in constant motion. Each variation in sea level, waves, currents, and sediment supply alters the land-sea interface. Beach sands move offshore, onshore, and along the shore in the direction of the prevailing longshore currents. In this way, sandy coasts continuously adjust to different tide, wave, and current conditions. The movement of sand by waves and currents reshapes the islands along the coast, and rising sea level causes the islands to migrate landward.

Despite such changes, barrier islands are of considerable environmental importance. The Outer Banks are home to diverse natural ecosystems that are adapted to the coastal environment. These islands can be harsh places for plants and animals. Their sandy soil is nutrient poor; hurricanes and northeast storms cause high winds, flooding, and sediment overwash; plants must tolerate salt spray and rapidly draining soils; and island resources limit terrestrial animals in both size and number. It is not surprising, therefore, that native species tend to be robust enough to endure these conditions. Many plants are specifically adapted to withstand salt spray and periodic saltwater flooding, while many are also succulent and can tolerate the islands' well-drained sandy soil. The principal forms of animal life include mammals, reptiles, and birds—the latter by far the most abundant. The Outer Banks provide an important stopover for birds on the Atlantic flyway, and many species inhabit the islands year round. In addition, Outer Banks beaches provide an important nesting habitat for five endangered or threatened sea turtle species.

European explorers discovered North Carolina's barrier islands in the 16th century, although the islands were not permanently settled until the middle 17th century. Prior to the mid-18th century, a few wealthy businessmen controlled most of the land on the Outer Banks. By the end of the Revolutionary War, however, this changed as the larger tracts of land were subdivided into small plots. By the early 19th century, shipbuilding and lumber industries were among the most successful, until forest resources were depleted. Eventually commercial fishing became more prominent, and it expanded considerably after the Civil War. By the time of the Great Depression, little industry existed on the Outer Banks. In response to the effects of a severe hurricane in 1933, the National Park Service and the Civilian Conservation Corps proposed a massive sand-fixation program to stabilize the moving sand because storm waves could sweep across the entire width of some sections of the islands from ocean to sound. Between 1933 and 1940, workers in this program constructed more than 900 kilometers (600 miles) of sand fencing on 185 kilometers (115 miles) of beach. To further stabilize the dunes, they also planted 13 million square meters (140 million square feet) of grass and 2.5 million seedlings, trees, and shrubs.

[1]University of Virginia, Charlottesville, VA

[2]U.S. Geological Survey, Reston, VA

In 1937, Congress authorized the Cape Hatteras National Seashore, which was completed in 1953. This seashore encompasses most of the Outer Banks between Nags Head and Ocracoke Inlet, except for several local villages and the Pea Island National Wildlife Refuge. The two primary reasons for its establishment were to preserve one of the world's best examples of a barrier island environment, and to minimize the impact of erosion that was becoming a serious problem. In 1966, Congress authorized the Cape Lookout National Seashore to ensure that Core and Shackleford Banks would not undergo major development and could be preserved in their natural state.

The rate of population growth along the Outer Banks in recent decades has been among the highest in North Carolina. Between 1990 and 2010, the permanent population grew from approximately 48,000 to nearly 58,000, an increase of 21 percent. More important, however, has been the growth in vacationers. In 1980, prior to a boom in vacation-home development, roughly 100,000 to 150,000 people visited the Outer Banks each week during the summer. In 2008, this number had grown to more than a quarter of a million visitors during a typical week. Municipalities now need to provide services to a population as much as six times as large as their permanent resident population.

Although human activities have dominated the landscape changes observed on the Outer Banks for the past century or two, these changes must be understood in the context of the prevailing atmospheric, oceanic, and geologic processes that have governed the form and function of these islands for thousands of years. It is these natural processes that imbue the Outer Banks with their unique and dichotomous qualities of tranquility and tumult. In the presence of human occupation, it is these processes that make the islands one of the highest natural-hazard risk zones along the entire Eastern Seaboard of the United States.

Introduction

In Nature's infinite
book of secrecy
A little I can read

—William Shakespeare (1606–1607), Antony and Cleopatra

The Outer Banks are a long arc of low sandy islands off the coast of North Carolina. The islands are prime examples of the 300 barrier islands rimming the Atlantic and Gulf coasts of the United States, formed where the relatively flat Atlantic and Gulf coastal plains intersect a wide submarine continental shelf. Barrier islands form between the open ocean and mainland coast and are generally less than 5 kilometers (km) (3 miles (mi)) wide. Sand dunes are the highest topographic feature of these long, narrow islands, although they usually rise only 3 to 6 meters (m) (10 to 20 feet (ft)) above sea level. These low, sandy islands are among the most dynamic natural landscapes that people inhabit.

The Virginia–North Carolina border is the northern boundary of the Outer Banks, but experts differ on the southern terminus. Geologically distinct northern and southern provinces of Outer Banks islands lie offshore of the North Carolina coast. Islands and mainland converge at Cape Lookout (map poster and fig. 1), causing some geologists to define Cape Lookout as the southern terminus (S.R. Riggs, East Carolina University, personal commun., 2005). Other geologists use Bogue Inlet (slightly west of the map area of fig. 1) as the southern terminus, because it marks the end of Cape Lookout's lower "barrier limb" (Moslow and Heron, 1994). The State of North Carolina separates its coast into commercial areas, and its maps show the Outer Banks abutting the "Crystal Coast" along Core Banks on Cape Lookout National Seashore (North Carolina Department of Commerce, 2008). In this report, we use Beaufort Inlet (map poster), west of Shackleford Banks, which is "the south and west boundary of the area most widely thought of as the Outer Banks" (Stick, 1958). Thus, the Outer Banks extends a total distance of 345 km (215 mi).

The dynamic nature of beaches and dunes is part of the aesthetic and recreational appeal of Atlantic Coast barrier islands. Processes affecting the islands span time scales from hours to decades, and beaches vary during each 24-hour tidal cycle. Periodic storm surges, shoreline recession in response to long-term rise in sea level, shifts in storm tracks, and island-wide modifications associated with human activities all contribute to these changes. Storms may damage or destroy private landholdings and disrupt communication and transportation. Despite these problems, and with a few exceptions, development has proceeded as if barrier islands are stable or can be engineered to remain stable.

Figure 1. The Outer Banks of North Carolina.

The Outer Banks, particularly the ocean side, has always been a hazardous place to live. Early inhabitants recognized this fact and settled on the more stable parts of the islands well inland from the ocean. During the 20th century, the pattern of land use changed and buildings were constructed much closer to the ocean-side shoreline. Since the 1960s, an increase in development on the islands has exacerbated the situation. The year-round population increased from approximately 3,000 in 1960 to 35,000 in 2008; during the summer months, the total population may exceed 3 million. Three segments of the islands have attracted the majority of high-density growth: from south to north, Hatteras Village and Buxton; Roanoke Island, including the town of Manteo; and the strip of development extending from Nags Head to Duck and ending at Corolla.

Although some people settled some of the Atlantic and Gulf coast barrier islands as early as the colonial period and used others as sources of building materials for coastal defense sites during World War II, changing economic and social conditions following the war made the islands more desirable for development. However, time has not changed the natural processes and hazards associated with developing barrier islands. It is just as risky today as it was a century ago to build a house on shifting sand. The danger from hurricanes and severe northeast storms is just as great and, if one considers the increasing population density on some of the islands, the potential for disaster is even greater. Clearly, the desire to be near the water's edge has led growing numbers of people to disregard the greatly increased risk to life and property associated with inhabiting low-lying islands (fig. 2).

All barrier islands result from the interaction of sand and physical processes, a surplus of sand supplied to the coast, and waves large enough (generated by winds strong enough) to move that sand. Changes in any of these factors can alter the overall relationship. When undeveloped, barrier islands adapt to such changes through a process known as dynamic equilibrium. However, adding pavement and buildings to the islands hampers this natural adjustment, and changes in various natural physical processes can lead to abnormal adjustments that may destroy highways, homes, and businesses.

Figure 2 (facing page). Kitty Hawk, North Carolina, November 1981. *Photograph courtesy of the U.S. Army Corps of Engineers.*

The constant movement of sand by waves and currents constantly reshapes the islands along the coast, creating instability, and rising sea level causes the islands to migrate landward (Dolan, Hayden, and others, 1977). Despite such positional instability, however, barrier islands are of great environmental importance. The estuaries and sounds behind them are among the richest and most biologically productive ecosystems known: they provide nurseries, shelter, and food for many fish, shellfish, and wildlife species (Paerl and others, 2001).

The Federal Government has preserved some barrier islands in an undeveloped state. Ten of the United States' most scenic undisturbed islands or island groups have been set aside by the National Park Service as national seashores: they are (from north to south on the East Coast) Cape Cod, Fire Island, Assateague Island, Cape Hatteras, Cape Lookout, Cumberland Island, Canaveral, Gulf Islands, and Padre Island, and (in California) Point Reyes. Other coastal areas are preserved as national wildlife refuges. Many coastal states have at least one barrier island under such Federal protection. Along the Outer Banks, nearly two thirds of the total land area is preserved as national and state parks, seashores, and monuments. These preservation decisions ensure that future generations will have a natural coastal environment both to enjoy and to study.

Understanding the natural dynamics of barrier islands is key to recognizing and estimating both the short- and long-term hazards of living on them. This report summarizes how the barrier islands are formed, how they have changed, and why they will continue to change in spite of efforts to alter the natural processes that shape them. The Outer Banks of North Carolina are used as an example, but the principles outlined here are applicable to all barrier islands along the Atlantic and Gulf coasts.

Agents of Change in the Outer Banks

Barrier islands, such as the Outer Banks of North Carolina, are the destination of choice for millions of vacationers each year seeking tranquility in sun, surf, and sand. For many, the allure of these islands is tied to the calming and restorative properties of balmy breezes and the rhythmic sound of waves breaking along the shore. They seem so stable, so enduring. Yet, to geologists, barrier islands are among the least stable and shortest lived of all landforms.

The story of the Outer Banks is one of continuous and inexorable change; it is a saga of sand shifting over millennia and centuries in response to the forces of nature and, more recently, to the activities of people. Indeed, the dynamic nature of the Outer Banks provides the subtext for the material contained in this book. Although many factors contribute to changes on barrier islands, three in particular play a critical role: sea-level change, storms, and human habitation. It is useful, therefore, to introduce these three issues before proceeding into the body of the book.

About 15,000 years ago, the last of the Pleistocene glacial stages was nearing its end. At that time, sea level was approximately 110 m (360 ft) lower than today. Notably, the Outer Banks did not exist at that time and the shoreline of North Carolina was 80 to 120 k (50–75 mi) seaward of its present location. As climate began to warm during the transition from glacial to interglacial conditions, ice sheets and glaciers melted and, by about 8,000 years ago, sea level had risen rapidly to a position about 5 m (16 ft) lower than today. The rate of sea-level rise then slowed markedly and has continued at a relatively steady rate to its position today. It was this change from rapid to slow sea-level rise, coupled with a surplus of beach sand that had been continuously moving with the migrating shoreline as sea level rose, that enabled the Outer Banks to begin forming. Thus, the importance of sea-level rise on barrier islands is realized over very long periods of time, centuries to millennia.

During shorter time scales, such as days, weeks, and seasons, storms are the dominant agent of change along the Outer Banks. Coastal storms, whether tropical or extratropical, and the waves that they produce, move enormous amounts of sand offshore, alongshore, and across the shore as overwash. In just a couple of days, a hurricane or a winter season northeast storm (nor'easter) can cut an inlet through a narrow strip of island or erode enough sand to undermine a beachfront house. The typical northeast storm usually removes sand from the beach and deposits it temporarily onto an underwater bar close to shore. As fair weather and calm seas return during the ensuing weeks, that sand gets redeposited back onto the beach. In some years, however, storms are frequent enough that the sand does not return to the beach between storms. In such instances, sand may be transported far enough offshore during a winter season that it never returns to the beach, resulting in permanent beach erosion.

In between the long-term influence of sea-level change and the short-period effects (years to decades) of storms, human activities play a major role in altering the Outer Banks. The appearance of the islands as seen by visitors today differs remarkably from the islands that the Wright Brothers saw when they tested their aircraft designs at Kill Devil Hills more than a century ago. Then, the Outer Banks were barren isles with few people or permanent structures. Now, it is difficult to find any expanses of undeveloped or unaltered land outside the national parks and national seashores. Indeed, it would be difficult today for the Wright Brothers to find an appropriate location in which to duplicate their pioneering efforts. And these changes affect not only our visual impression of the landscape, but also how natural processes such as sand transport and inlet formation take place. Roads, houses, businesses, shopping centers, water treatment facilities, and golf courses, as well as dozens of other indicators of human habitation, exert a major influence on the manner in which the Outer Banks respond to natural forces acting in both long and short terms. That influence in important ways also tends to reduce the islands' natural ability to adjust to future events.

Barrier islands, when undisturbed, exist in a state of dynamic equilibrium. They get breached and overwashed, and they migrate in response to the high-energy processes of the atmosphere and ocean as sand moves unimpeded from the beach to the sound. They change, and the indigenous flora and fauna adapt to those changes. When people construct on barrier islands, however, dynamic equilibrium is disrupted because people, unlike flora and fauna, typically attempt to return the islands (that is, re-engineer them) to their prestorm conditions rather than by adjusting to the new conditions. They re-engineer, for instance, by returning sand deposited on roads to the beach and by repairing damaged buildings and roads. In some instances, new protective structures are erected to prevent damage from future storms. These efforts are an attempt to protect valuable real estate investments, to ensure that financial and recreational benefits continue to accrue. It is an understandable response, but it is one that conflicts with the intrinsic instability of barrier islands. During decades to centuries, it may be that the financial cost of attempting to keep these islands in an apparently stable condition becomes unjustifiable.

Indeed, we may ultimately recognize the wisdom of Francis Bacon who in 1620 made the following two observations: First, ***Man, being the servant and interpreter of Nature, can do and understand so much and so much only as he has observed in fact or in thought of the course of nature. Beyond this he neither knows anything nor can do anything.*** Second, and more succinctly, ***Nature, to be commanded, must be obeyed.***

Part I: Natural History of the Outer Banks

Barrier Island Landforms: An Introduction to Geographic Features of the Outer Banks

The Atlantic and Gulf Coastal Plains are relatively flat and slope gently seaward to a wide submarine continental shelf. Wind, waves, and storms that combine with abundant sediment sometimes create barrier islands at the dynamic interface of land, water, and atmosphere. Composed almost entirely of sand, barrier islands are among Earth's most active landforms partly because their physical form (their morphology) responds to countless variations in sea level, wave action, storm surge, and sediment supply. Because the same geologic conditions create all barrier islands, most share common geographic features, such as beaches, inlets, storm washover deposits, sounds, and sand dunes.

Barrier islands differ in geometry, but they are usually 3 to 30 km (2 to 20 mi) offshore and about 1.5 to 4.5 km wide (1 to 3 mi) wide. Sand dunes, which are usually the islands' tallest topographic feature, are only 3 to 6 m (10 to 20 ft) high. Jockey's Ridge dune near Nags Head, NC, the tallest dune system on the East Coast of the United States, has a maximum height of 24 to 30 m (80 to 100 ft).

. . . these coastal forms merge and blend in a shifting, kaleidoscopic pattern in which there is no finality, no ultimate and fixed reality— earth becoming as fluid as the sea itself.

—Rachel Carson (1955), The Edge of the Sea

Beaches

Beaches are loose deposits of sediment that accumulate along the boundary of large bodies of water. Waves, and the currents they produce when they reach the shallow water of the coast, combine with tides and storm surges to create beaches. Processes creating a beach begin offshore with waves moving landward. Where water is about 10 m (30 ft) deep, waves approaching the seaward face of the Outer Banks begin to feel bottom; as they move landward into shallower water they stir up sand and grow higher, and near the shore the waves break and drop their sand. The beach itself extends landward from the point of mean low water to either the beginning of permanent vegetation or to the next distinct geographic feature, such as a dune (fig. 3), and it is of two parts called the foreshore and the backshore. The tidal range, slope of the land, wave conditions, and volume of available sand combine to help determine how wide a beach will be. The beach's natural sandy border helps to protect the main portion of the island from storms, just as the barrier island itself helps to protect the mainland from these same storms.

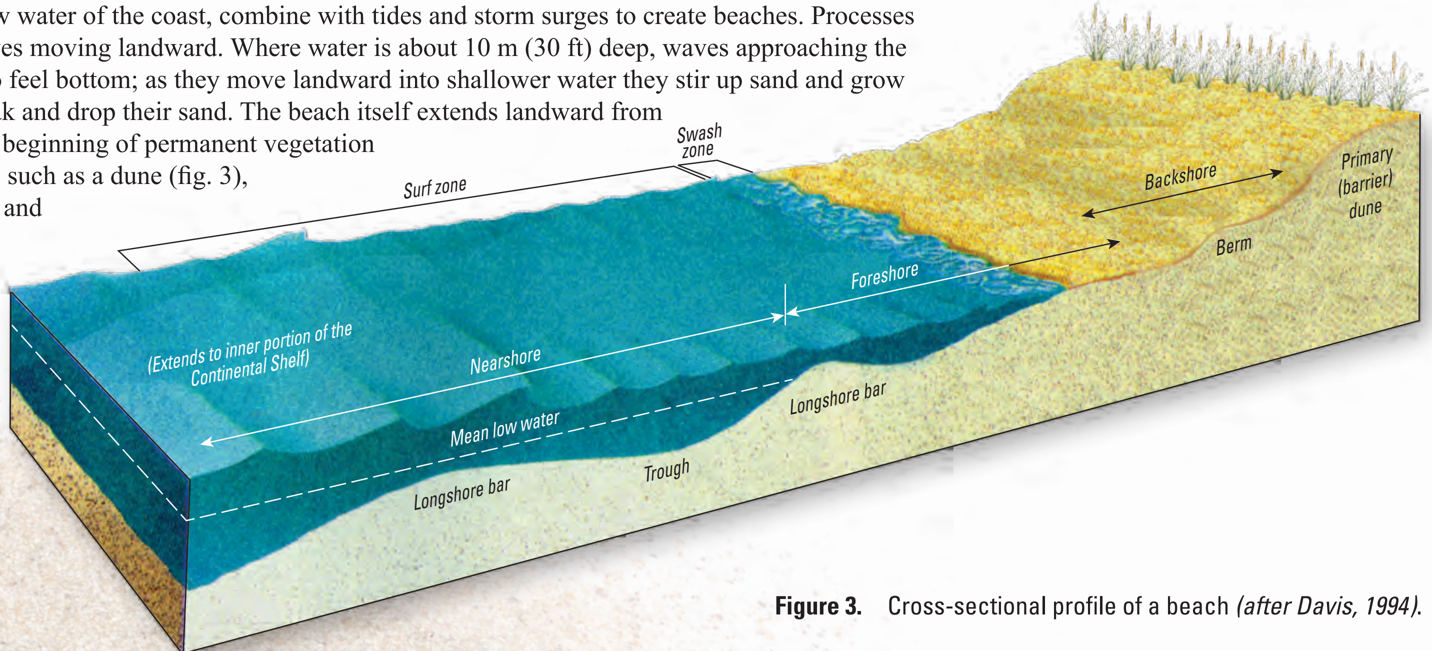


Figure 3. Cross-sectional profile of a beach *(after Davis, 1994)*.

Inlets

An inlet is a break or opening in the barrier island that allows seawater to flow from the ocean side into the sound between the mainland and the barrier island. Although they are called "inlets," from the standpoint of their actual function, inlets could just as well be called "outlets." In addition to providing a return path for ocean water that floods through inlets during storms and high lunar tides, they also accommodate all freshwater that flows from rivers on the mainland into the sounds and then release it into the ocean. Physical factors such as tidal range, distance from the primary sediment source, and the geology underlying the island control the number of inlets. In the Outer Banks' wave-dominated environments, longshore currents cause the inlets to migrate in the direction of drift relatively rapidly (Moslow and Heron, 1994).

In the 208 km (129 mi) between the Virginia–North Carolina border and the southern tip of Hatteras Island, Oregon Inlet is the only "outlet" interrupting the islands. In the southern 124 km (77 mi) from Hatteras Island to Shackleford Banks, the number of inlets increases to six—Hatteras, Ocracoke, Old Drum, New Drum, Barden, and Beaufort (fig. 4).

Washover Deposits

Storms and high waves advancing inland beyond the active beach zone may generate overwash deposits when wave runup destroys the primary dune and deposits sediment in areas normally associated with wind-blown deposits. The water and sediment mixture that penetrates inland is called overwash, and the resultant deposit is known as a washover fan (fig. 5). Major or repeated overwash events produce larger depositional areas known as washover flats.

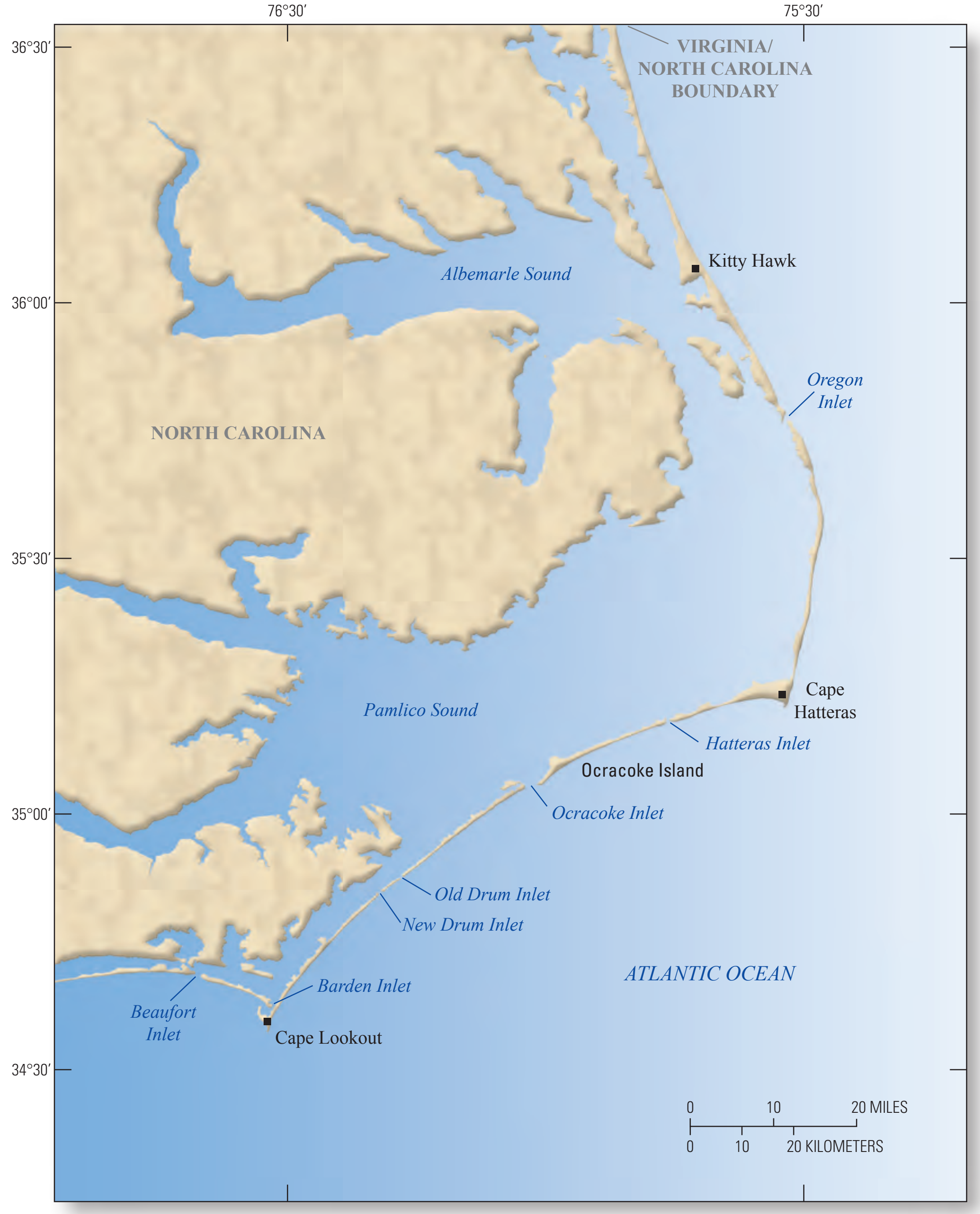
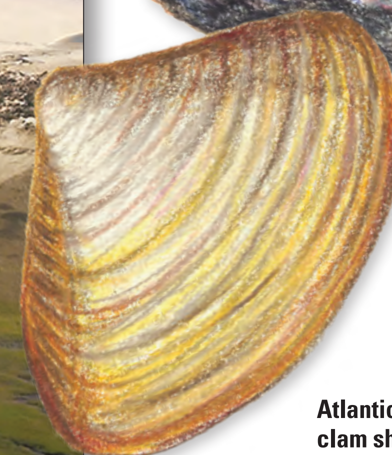


Figure 4. Modern inlets of North Carolina's Outer Banks.

Figure 5. Washover fans on northeast Ocracoke Island, North Carolina, September 24, 2003, after Hurricane Isabel. Earthmoving equipment in the upper right corner of the photograph provides a scale. *Photograph courtesy of Michael Halminski.*

Eastern oyster (*Crassostrea virginica*)

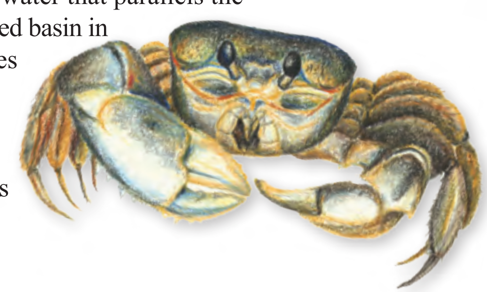


Atlantic surf clam shell (*Spisula solidissima*)

Knobbed whelk shell (*Busycon carica*)

Sounds

Currituck, Albemarle, Pamlico, Core, and Back Sounds separate the Outer Banks from the mainland, and Roanoke and Croatan Sounds border Roanoke Island (see map poster). “Sound” is a rather general geographic term. It may refer to a relatively long arm of water that provides a channel between the islands and the mainland or between two larger bodies of water. Outer Banks sounds can be divided into back barrier bays and estuaries. A back barrier bay is a narrow, elongate body of water that parallels the coast (Moslow and Heron, 1994); it does not receive direct inflow from a large river. An estuary is a partly enclosed basin in which freshwater from the widening mouth of a river mixes with ocean water. Salinity in an estuary increases away from the freshwater source. Outer Banks islands protect the sounds from ocean waves and storms. In this calmer environment, submerged aquatic vegetation grows along the bottom and provides an important habitat for many marine species. Pamlico Sound (map poster and fig. 1) is a major fish and shellfish nursery on the Atlantic seaboard (Paerl and others, 2001) and is the second-largest estuarine ecosystem in the United States (Chesapeake Bay, bordered by Maryland and Virginia to the north, is the largest).



Ghost crab (*Ocypode quadrata*)

Dunes

Sandy hills—dunes—of various sizes characterize Outer Banks' topography landward of the beach (fig. 6). Strong prevailing easterly winds transport most dune sand to the west across the beach and deposit it on the island's interior, either in washover flats or in vegetated areas. Here, plants or other structures that interrupt the wind may stabilize the sand, or wind may redistribute it. Large dunes sometimes form in areas with wide, active beaches and strong prevailing winds. From the 1930s to the 1970s, Federal programs created most of the high beach foredunes (also called barrier or primary dunes) along much of the northern Outer Banks' Atlantic side in an effort to stabilize the islands.

Capes and Shoals

The distinctive shape of Cape Hatteras and Cape Lookout create the Outer Banks' trademark appearance. Capes are large cuspate landforms that project into the ocean and break or change the larger trend of the coastline.

How did the capes form? Scientists attempting to answer this question have presented several explanations based on various observations. Because the Outer Banks capes appear to be related to smaller, sinuous coastal landforms, the capes may reflect "long-term trends in coastal currents" and "short-term variation in the state of the sea" (Dolan and Ferm, 1968). Underlying erosion-resistant rock may have helped to anchor the cape and the overall configuration of the cape island (Blackwelder and others, 1982). More recently, it was proposed that the combination of shoreline orientation and the direction of incoming waves could create shoreline instabilities that developed into the North Carolina capes (Ashton and others, 2001).

Both Cape Hatteras and Cape Lookout (map poster) are associated with very large, well-developed underwater shoals. Diamond Shoals at Cape Hatteras and Cape Lookout Shoals at Cape Lookout are many kilometers long and are oriented nearly perpendicular to the adjacent shoreline. The shoals continually shift in response to ocean dynamics and create a substantial navigation hazard.

Figure 6. Dunes at Cape Hatteras, North Carolina, 1975. *Photograph by Robert Dolan.*

Barrier Island Dynamics: Forces Shaping the Outer Banks

To me, the sea is a continual miracle,

The fishes that swim—the rocks—the motion of the waves—the ships with men in them,

What stranger miracles are there?

—Walt Whitman (1856), Miracles

The physical interface between land and sea is in constant motion. On sandy coasts, each variation in sea level, waves, currents, and sediment supply alters the interface. Beach sands move offshore, onshore, and in the direction of prevailing longshore currents. In this way, sandy coasts constantly adjust to different tide, wave, and current conditions. Periodic phases of erosion and deposition are superimposed on a trend of rising sea level that began more than 10,000 years ago as Ice Age glaciers began melting. This long-term rise submerges the beach, causes shoreline recession, and forces the barrier islands landward. A trench cut through a dune (fig. 7) shows that the Outer Banks are an assemblage of sedimentary layers, each made up of different-sized particles that indicate their source and the processes that moved them. These deposits consist primarily of medium-sized quartz sand (about ⅓ millimeter diameter) and a smaller percentage of heavy mineral grains, such as garnet and amphibole, as well as gravels and shell fragments. Material composing the island is carried and deposited, layer upon layer, primarily by storm overwash or by currents flowing through inlets. Embedded within the layers of beach material are units of well-sorted finer sands and silts transported by wind. An island's configuration reflects the interaction of onshore deposits and longshore sand transport.

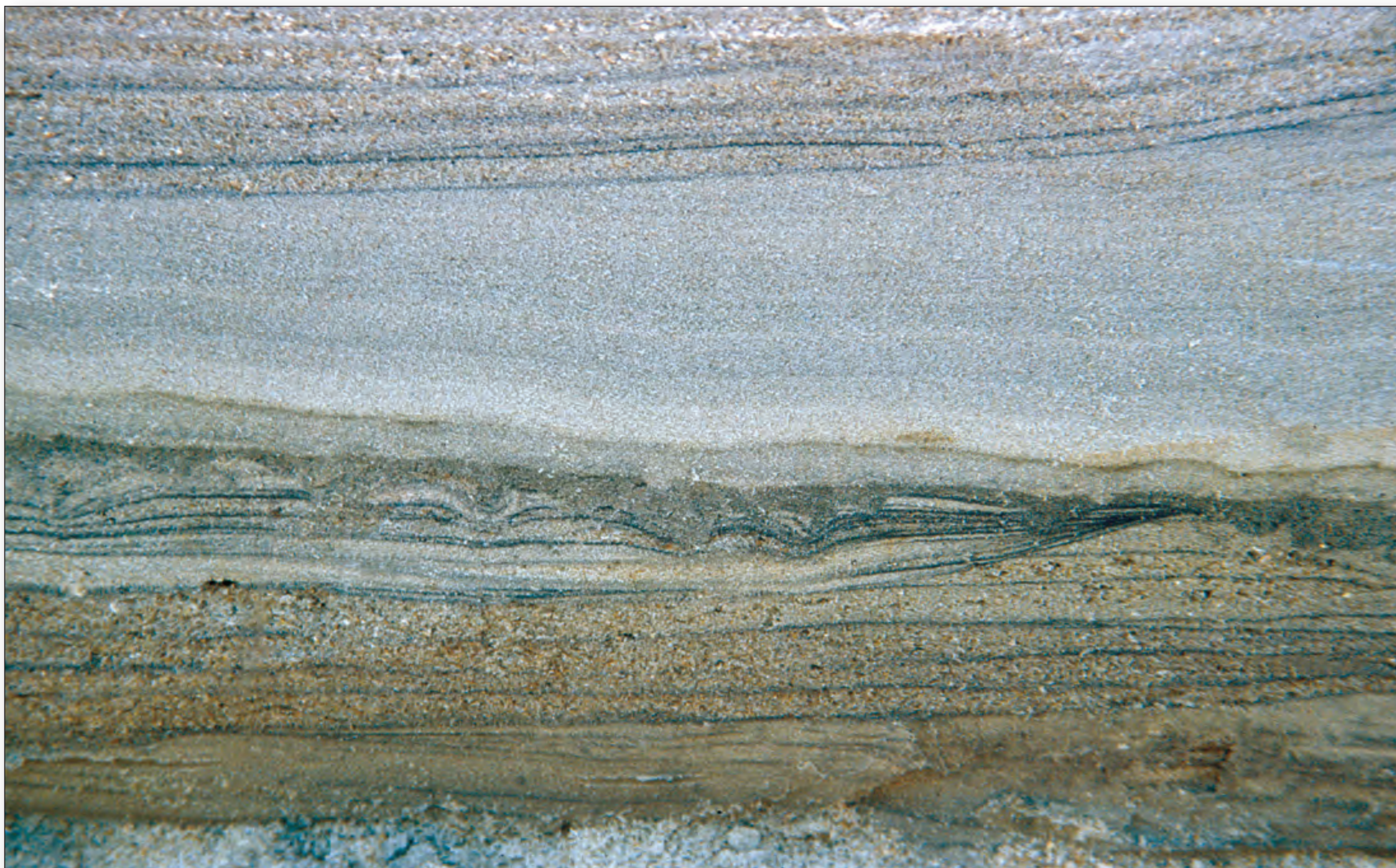


Figure 7. Each sand grain tells a story. Barrier islands are composed of sedimentary layers; each layer reflects the hydraulic processes that formed it. *Photograph by Robert Dolan*.

Complex, interrelated processes shape and reshape the sand deposits of the Outer Banks. Three factors control these changes: the amount and attributes of sediment, the magnitude of natural processes, and the stability of sea level.

To summarize, the physical processes acting upon the islands can be placed into two categories:

- Oceanic and atmospheric forces—wind, waves, tides, storms, and sea-level rise
- Sedimentary processes—principally longshore sediment transport, inlet dynamics, overwash, and wind distribution of sediment.

Oceanic and atmospheric forces are the basic forces acting upon the islands. These basic forces combine to move sediment. The dominant sedimentary processes on the Outer Banks are longshore sediment transport, inlet dynamics, overwash, and wind (aeolian) distribution (fig. 8). These processes move sand along and across the islands.

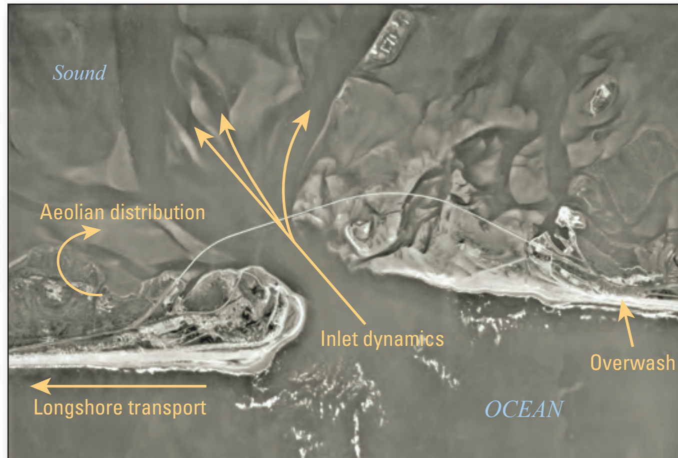


Figure 8. The four primary methods of sediment transport on barrier islands.

Oceanic and Atmospheric Forces

Wind

Oceanic and atmospheric forces are the driving variables of the Outer Banks. Differential heating of the atmosphere creates differences in air pressure above the world's oceans and causes the atmosphere to move back and forth like water in a basin. Combined with Earth's rotation and uneven distribution of land and water, a complex wind system develops that is constantly striving for atmospheric equilibrium. Part of this energy is transferred to the ocean's surface, creating waves.

Similarly, uneven heating of land and water creates local offshore and onshore winds (land breezes and sea breezes). The flat barrier-island topography and generally low vegetation provide little to break winds that steadily blow in from the ocean. For this reason, barrier islands are especially susceptible to destructive storm winds (fig. 9).

Figure 9. Wind from Hurricane Emily snapped these trees in Buxton, North Carolina, on September 1, 1993. *Photograph courtesy of the U.S. Army Corps of Engineers.*

Waves

Ocean waves are wind-driven, undulating forms that move across the ocean surface. As wind moves across the surface of the ocean, it transfers energy to the water surface through friction. That friction generates waves; waves move downwind through the ocean and, when the waves eventually break, they transfer their energy to the shore.

Other kinds of energy-transfer waves also exist. Tides are a type of long-wavelength, long-period wave induced by gravity. Tsunamis are waves caused by a transfer of energy through tectonic movement of the Earth's crust. On a smaller scale, a wake forms by transfer of energy from a moving boat to the water.

We refer to the Outer Banks as wave-dominated microtidal barrier islands because waves, rather than tides, do most of the work that shapes the islands. ("Microtidal" refers to tides that rise and fall less than 2 m (6 ft)). Microtidal islands are long and narrow and have few inlets. If the Outer Banks' tidal range were greater than 2 m (6 ft), tidal effects would dominate the configuration of the islands and create more permanent inlets and wider islands.

The size and speed of waves depend on three factors, all related to wind: its speed, its duration (how long it has been blowing), and its fetch (how far it has blown in one direction). The larger any of these factors, the higher the waves that will be produced.

As these wind processes create and enlarge waves, other factors work to limit wave size. The steepness of a wave is limited regardless of wind velocity. When the ratio of wave height to wavelength reaches 1:7, the wave cannot maintain its form and it collapses. Water depth also limits wave height. As the rolling motion of waves approaches the shore, the increasingly shallow bottom causes the waves to slow and to compress each other, making them steeper and reducing their wavelength. A deep-water wave moves in water deep enough so that it does not "feel" the bottom. For this condition to exist, generally the water depth is equal to or greater than half the wavelength. The wave collapses or breaks when the water depth near the shore approximately equals the wave height (Komar, 1998).

Island morphology may change markedly under different wave conditions. Normal fair-weather conditions generate relatively stable atmospheric and oceanic conditions. Sediment movement by waves and currents is also stable, and changes to beaches and barrier islands are modest. Storms, however, disrupt any preexisting equilibrium. Storm winds increase wave height. Because wave energy is proportional to the square of the wave height, wave energy increases exponentially as wave height increases. When waves reach shore, this energy is expended in reshaping of the island. The Outer Banks' shoreline configuration, combined with a narrow continental shelf, gives rise to a wave-energy regime higher than that of any other barrier shoreline on the East Coast of the United States (Moslow and Heron, 1994).

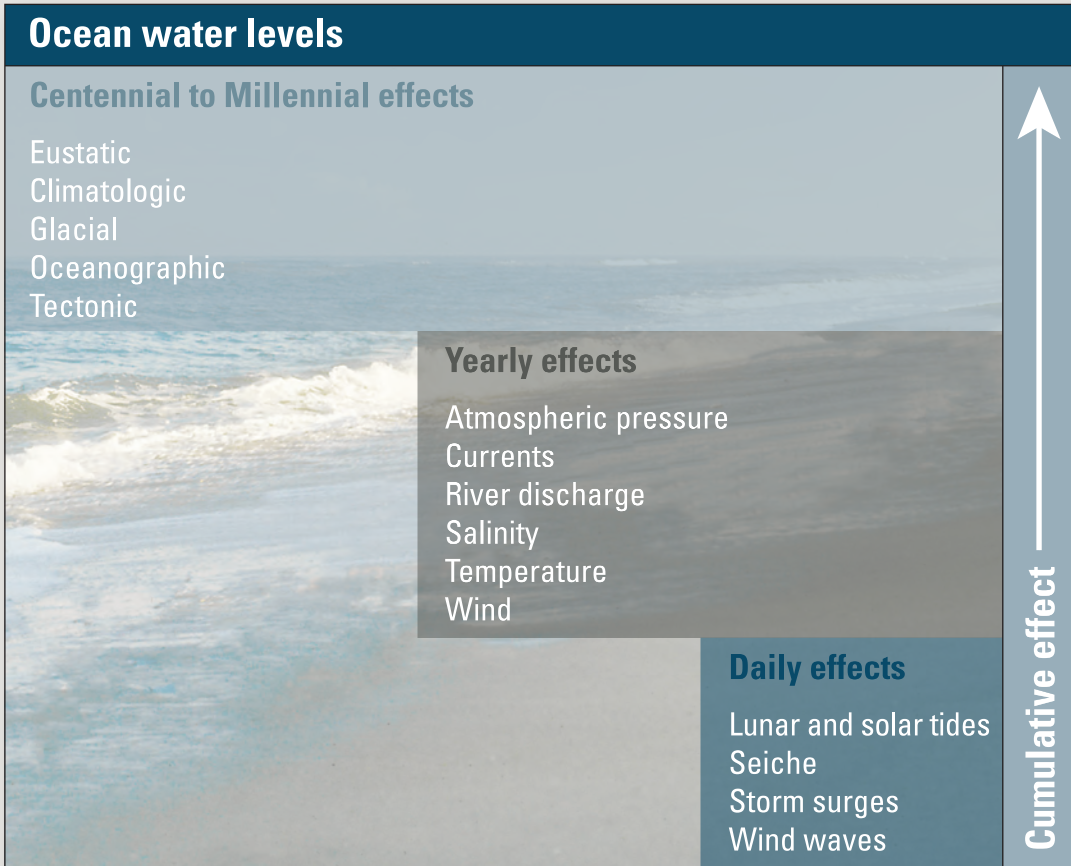


Figure 10. Factors affecting ocean water level, and the time scales at which they operate.

Tides

The ocean's water level constantly changes. Tides, storm waves, storm surges, and long-term sea-level fluctuations all contribute to variations in water level (fig. 10). Astronomical tides are long-wavelength, long-period waves caused by the gravitational pull of the Sun and Moon on the Earth's oceans. Astronomical tides along the Outer Banks rise twice daily, 12 hours and 25 minutes apart, with an average range of about 1 m (3.3 ft) (fig. 11).

Tides alone have little effect on sediment transport. When storm surge and high waves are superimposed, however, the daily elevation and depression of the water level can transport large volumes of sediment (fig. 12). In addition, tides cause the ocean's wave action to migrate up and down the beach face, exposing more of the beach to direct wave action and adding complexity to geomorphic processes.

The Sun, Moon, and Earth align in a straight line once every 14 days, combining their gravitational pull and producing a spring tide ("spring" here refers to the rising or welling of water, rather than the season). During a spring tide, high tides are approximately 20 percent higher than usual and low tides are lower than at any other point during a normal cycle. Higher tides mean deeper water that allows larger, more energetic waves to reach the coast. Conversely, when the Sun, Moon, and Earth align to form a 90-degree angle, some of their gravitational effects cancel. This configuration produces a neap tide that has the smallest tidal range in a normal tidal cycle. Two spring tides and two neap tides occur in every 28-day cycle of the Moon. The average elevation of the water surface of spring and neap tides differs by about 20 percent.

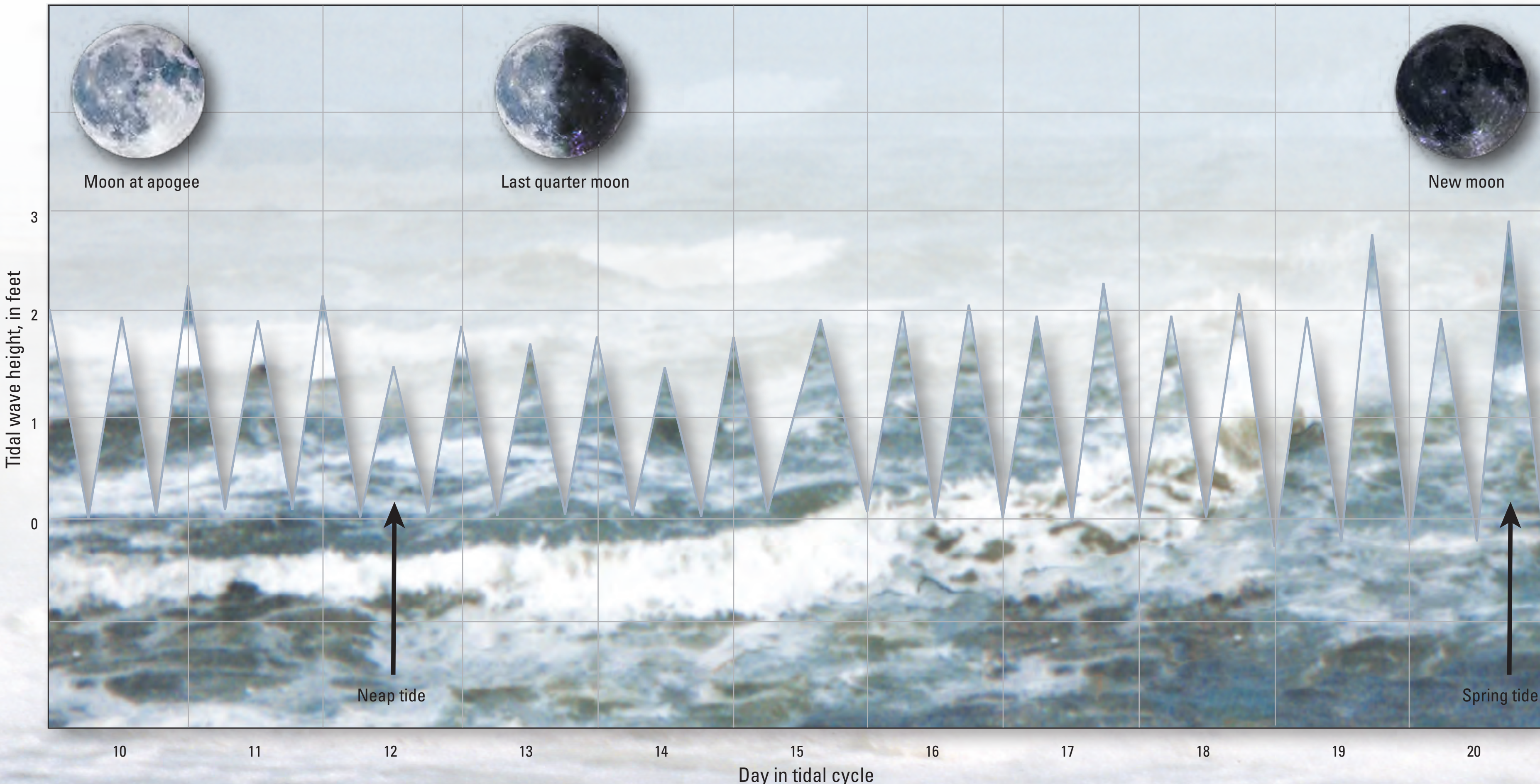


Figure 11. Representative tidal curve for Hampton Roads, Virginia. The tide is semidiurnal and varies conspicuously following changes in the Moon's phase. Tidal range for the Outer Banks is 0.6 to 1.2 meters (2 to 4 feet).

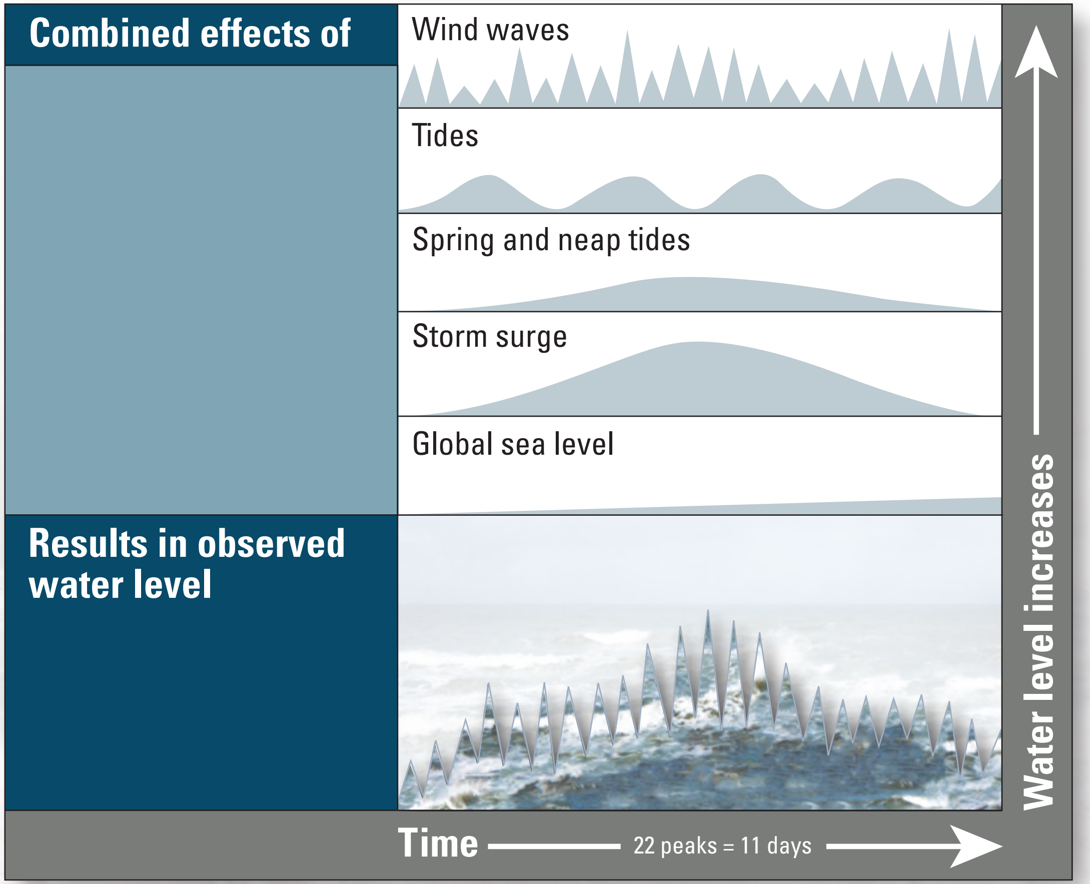
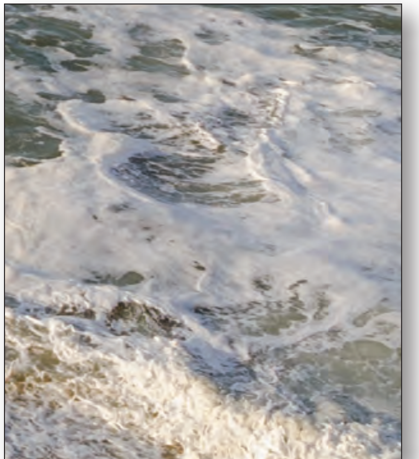


Figure 12. Many factors, throughout a range of time scales, combine to create the observed sea level.

In addition to the alignment of Sun, Earth, and Moon, the Moon's elliptical path around the Earth also affects the tides. Once every 28 days, the Moon is at its closest point to Earth (perigee), and also once monthly the Moon is at its farthest point from Earth (apogee). Three or four times a year, the spring tide coincides with the Moon's perigee, resulting in a higher-than-average perigean spring tide.

A perigean spring tide that coincides with a storm increases the destructive effects of storm surge in two important ways. First, the tide's higher water level increases the reach of the storm surge. Second, horizontal water currents flow faster than usual during a perigean spring tide. These faster currents are easily entrained by storm winds (Wood, 1986). Storm-wind friction against the water surface during a perigean spring tide is especially effective in raising the tide level and thereby flooding the coast and low-lying regions. Many catastrophic storms, such as the Ash Wednesday northeast storm of March 1962, occurred during perigean spring tides.



Storms

Processes that build and erode barrier islands span time scales from hours to decades to millennia, and each process has its own effect. The unusually high winds and water levels associated with storms intensify the inshore processes previously described, and they can reshape an island and damage constructed infrastructure much more quickly than fair-weather conditions would. The higher a wave and the longer a storm lasts, the greater the reshaping. Moreover, flooding from storms can cause atypically high runoff of freshwater and harmful chemicals into the sounds that, in turn, alters the habitat of flora and fauna that live there (Paerl and others, 2001).

Thus, storm winds and waves reconfigure the islands to reflect a storm's energy (fig. 13). Although it is well established that coastal storms produce change on decadal scales and smaller, it is less well understood how storms contribute to persistent changes on the barrier islands. After a storm abates, normal fair-weather waves begin reshaping the island again, and most beaches eventually regain most of their before-the-storm configuration.

Storm Surge

A storm surge is the difference between the predicted tide and the higher observed water level. It results from strong onshore winds or from reduced atmospheric pressure. Storm surge can multiply the intensity of changes that storm waves produce because, in effect, it raises the ocean's water level and moves it inland. The encroaching ocean reaches areas normally protected from wave action and can transform them quickly. If the storm surge completely submerges higher sections of beach, then waves mobilize and transport sediment more easily. After the storm passes, excess water on land returns to the sea (as a "surge ebb"). The surge ebb can move beach sand and storm debris offshore, modify the shape of existing inlets, and cut new inlets. Researchers investigate the details of storm surges to try to discern storminess trends during the past century.

Figure 13. Storm waves cutting into Outer Banks beach, reconfiguring it to reflect the higher energy conditions, March 1989. *Photograph by Sarah Spink Downing.*

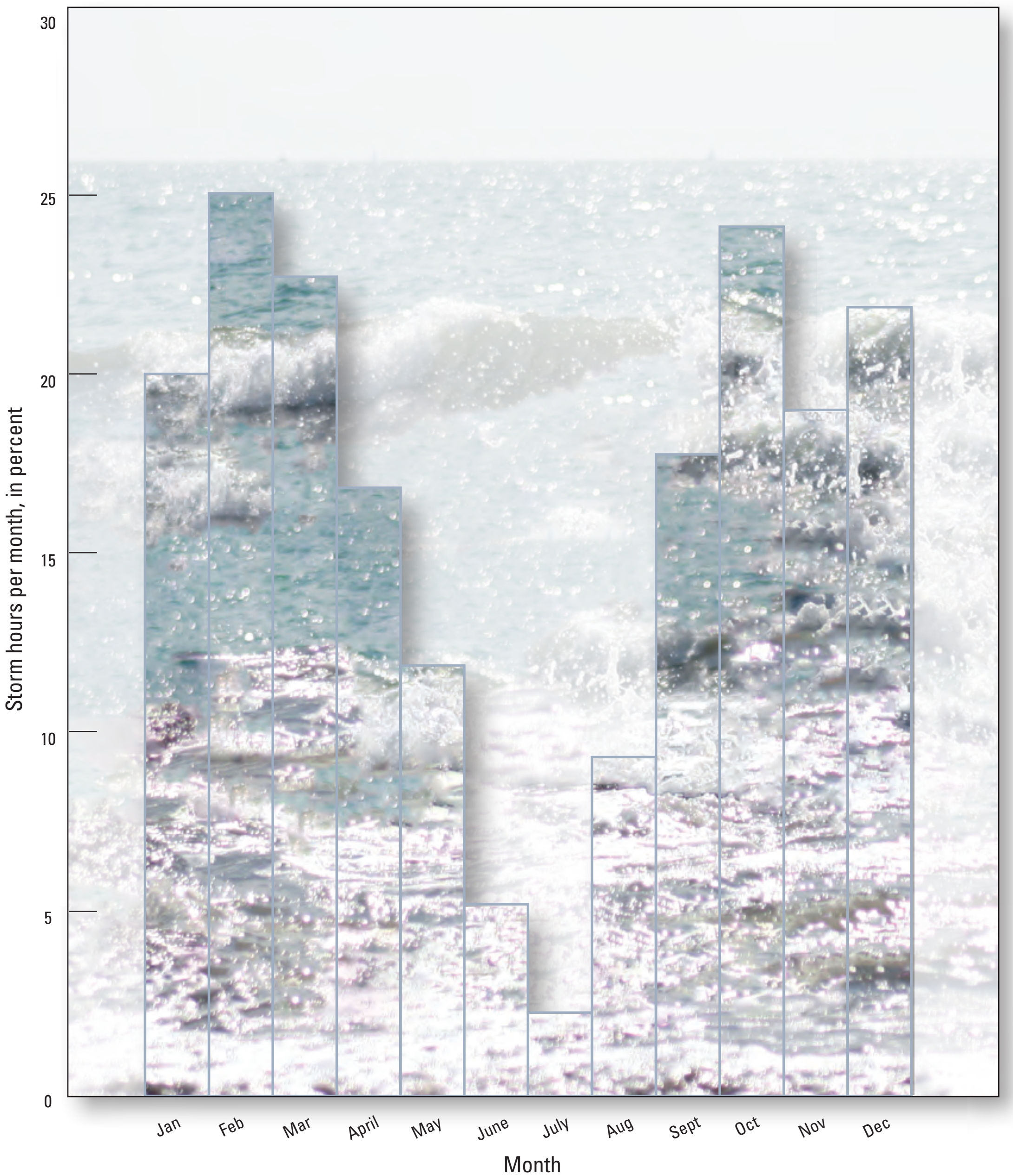


Figure 14. Monthly storminess at Duck, North Carolina, interpreted from wave height and duration data in water 18 meters (59 feet) deep.

Outer Banks Storms, 1985–2004

Waves classified as storm waves on the Outer Banks meet two criteria: they are at least 1.5 m (5 ft) high, and they travel in water deep enough that interaction with the ocean bottom does not alter their shape (Dolan and Davis, 1992). Because directly measured wave details are not always available, analysts determine deep-water wave heights after the fact by using other data. On the Outer Banks, tropical cyclones and extratropical northeast storms are the two types of storms that usually create waves large enough to be classified as storm waves. (Both types of storm originate over the ocean east of the East Coast, cover a large area, have a low-pressure center, and produce intense rain.)

Since 1985, The U.S. Army Corps of Engineers Field Research Facility in Duck, NC, has collected data on waves in water 18 m (59 ft) deep. Such waves constitute shallow transitional waves, rather than the deep-water waves analyzed by previous studies. If the 1.5 m (5 ft) wave-height criterion is applied to water of this depth, then data from 1985 to 2004 indicate an average of 60.3 storms per year at Duck. Of these, about 13 percent are tropical storms and the remaining 87 percent are mostly northeast storms. The analysis also shows that October and February are the stormiest months, when storms are present about 24 percent and 25 percent of the time, respectively (fig. 14). June and July are the mildest months, when storms occur 5 percent and 2 percent of the time, respectively.

Sorting the storms in this data set by significant wave height (H_{mo}) makes it possible to estimate return periods, a measure of how often waves of a specific height can be expected. A static return period is based solely on previous occurrences of H_{mo}. Dynamic return periods can be created by using climate models, which incorporate factors such as climatic variations, known forecasting errors, and the geologic record to model more accurately the probable occurrence of natural phenomena in a specific location.

Table 1. The original Saffir-Simpson Hurricane Scale (Simpson, 1974) has been widely used to categorize hurricane intensity. In 2012, the National Hurricane Center of the National Oceanic and Atmospheric Administration began categorizing hurricanes on the basis of sustained wind speed alone *(Schott and others, 2012).*

[>, greater than; <, less than]

Category	Central pressure (millibars)	Sustained winds (miles per hour)	Storm surge (feet)	Property damage
1	>980	74–95	4–5	Minimal.
2	965–979	96–110	6–8	Moderate.
3	945–964	111–129	9–12	Extensive.
4	920–944	130–156	13–18	Extreme.
5	<920	≥157	>18	Catastrophic.

Hurricanes on the Outer Banks

In the Northern Hemisphere, tropical cyclones originate over water typically between 10° and 20° of latitude, where the water temperature is at least 26.5°C (80°F) and the air near the surface has a counterclockwise (that is, cyclonic) spin throughout a wide area (fig. 15). As warm moist air in the region rises, it cools and condenses into clouds. Surrounding air near the ocean surface rushes in to fill the area left vacant by the rising air and, gradually, a vertical circulation begins: air converges at the surface and diverges aloft. If certain conditions remain in place (for example, very warm sea-surface temperatures and low wind shear aloft), the system will grow into a tropical storm (Pielke and Pielke, 1997).

Meteorologists classify these storms by using numerous physical characteristics, such as atmospheric pressure or rainfall. However, the standard criterion is sustained wind speed, which is the average wind speed for a one-minute period measured approximately 10 m (33 ft) above the surface. When sustained winds in a well-defined tropical cyclone reach 74 miles per hour (mph) (119 kilometers per hour (km/h) or 64 knots (nautical miles per hour)) the storm is classified as a Category 1 hurricane on the Saffir-Simpson Hurricane Scale (table 1; Simpson, 1974).

In addition to high winds, hurricanes generate large waves, torrential rain, and severe thunderstorms. Although improved weather forecasting and mass communication have sharply decreased deaths caused by hurricanes, catastrophic loss of life remains a risk in coastal areas, as demonstrated by Hurricane Andrew in 1992. Like other vulnerable communities, those on the Outer Banks formulate, maintain, and execute proper preparedness plans to reduce this possibility (Jarrell and others, 2001). Although mortality associated with hurricanes in the United States has decreased in recent decades, property damage has increased (fig. 16) as development has continued in coastal areas (Blake and others, 2011).

The National Hurricane Center in Miami, FL, manages the most complete set of data about tropical storms recorded since 1851. These data include tracks showing where each storm traveled and best estimates of wind speeds and barometric pressure in 6-hour increments. A detailed report on tropical cyclones since 1958 is also available. The State Climate Office of North Carolina maintains information about hurricanes and tropical storms that have struck North Carolina in both modern and historic times.

Between 1851 and 2004, 18 hurricanes made landfall on the Outer Banks (table 2) ("landfall" is here defined as the point at which at least half the hurricane's eyewall crosses land). Ten additional storms did not make landfall but generated sustained hurricane-force winds or gusts on the islands (table 3). Information from tables 2 and 3 indicates that the probability of hurricane winds on the Outer Banks in any given year is around 18 percent. Historically, a hurricane with wind speeds similar to those of Hurricane Isabel in 2003, a Category 2 on the Saffir-Simpson scale, will strike the Outer Banks an average of once each 14 years. A severe hurricane of Category 4 or 5 is unusual: it has been recorded only once in the 154-year record.

Scientific reports about storms before 1851 are rare. Most information from this period is anecdotal and is based on eyewitness accounts—such as the information about historical hurricanes on the islands from the time of Sir Francis Drake's settlements (beginning in 1585) through 1846 (table 4). In addition, the following two sections review two noteworthy and more recent hurricanes, Dennis and Isabel.

Figure 15. Hurricane clouds superposed on map of eastern United States. *Image courtesy of the National Aeronautics and Space Administration (NASA).*

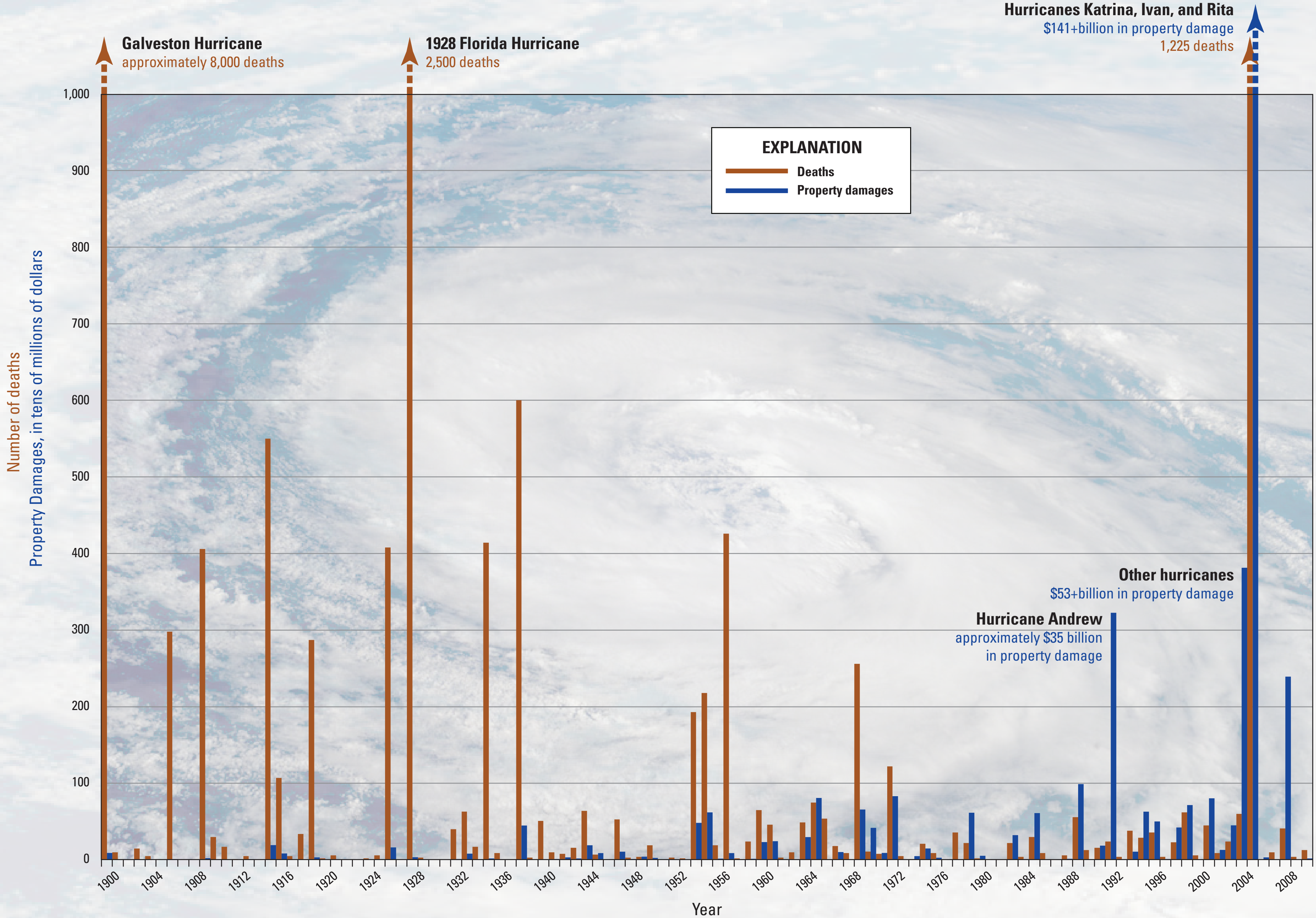
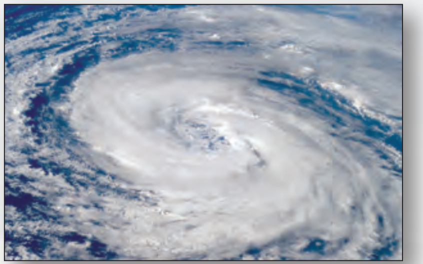


Figure 16. Deaths caused by hurricanes in the United States decreased during the 20th century, while damages to property increased *(data from Jarrell and others, 2001).*

Table 2. Hurricanes that made landfall (direct hit) on North Carolina's Outer Banks,1851–2004.

[Listed in descending order of wind speed; wind speed and landfall location approximate. mph, miles per hour; Category, hurricane category on Saffir-Simpson Hurricane Scale]

Wind speed (mph)	Name	Landfall			Notes
		Year	Date	Location	
				Category 4 hurricane	
132	San Ciraco hurricane	1899	Aug. 16	Hatteras	After severe damage, residents of Diamond City on Shackleford Banks abandoned the community.
				Category 3 hurricane	
115	None known	1904	Nov. 13	Hatteras	Four crew members drowned when New Inlet Lifesaving Station swept away.
115	Storm of '33	1933	Sept. 16	Ocracoke	Drum Inlet opened as Core Banks overwashed from sound to ocean.
				Category 2 hurricane	
109	Great hurricane of 1879	1879	Aug. 18	Near Virginia border	Initial North Carolina landfall near Morehead City as a Category 3 storm; significant effect on the Outer Banks.
106	Donna	1960	Sept. 12	Duck	Initial landfall in Florida as a Category 4 storm.
104	None known	1857	Sept. 13	Hatteras	Estimated 425 lives lost when S.S. *Central America* sank 200 miles off Carolina coast.
104	Barbara	1953	Aug. 13	Okracoke	National Hurricane Center began assigning women's names to hurricanes in 1953.
104	Gloria	1985	Sept. 26	Hatteras	Receding lunar tide combined with rapid storm movement reduced damage.
104	Isabel	2003	Sept. 18	Drum Inlet	Generated record highest waves at the U.S. Army Corps of Engineers Field Research Facility and widespread property damage.
98	Carol	1954	Aug. 31	Hatteras	Strongest storm winds were east of the Outer Banks, reducing island damage.
98	None known	1933	Aug. 23	Hatteras	First of two destructive storms to hit the Outer Banks within one month.
				Category 1 hurricane	
81	None known	1885	Aug. 26	Rodanthe	Initial landfall near southern South Carolina as a Category 3 storm.
81	None known	1908	July 31	Oregon Inlet	Initial landfall near Morehead as a Category 2 storm.
81	None known	1913	Sept. 3	Hatteras	Extensive flooding when storm pushed Pamlico sound's waters inland.
81	Connie	1955	Aug. 12	Core Banks	First of three hurricanes to hit North Carolina in a 6-week period.
81	Bonnie	1998	Aug. 28	Kill Devil Hill	Initial landfall near Cape Fear as a Category 3 storm.
75	Charley	1986	Sept. 18	Carova Beach	Initial landfall south of the Outer Banks, then moved through Pamlico Sound across the northern Outer Banks as a minimal Category 1 storm.
75	None known	1901	July 11	Hatteras	Highest winds reported at Hatteras; no reports of damage.



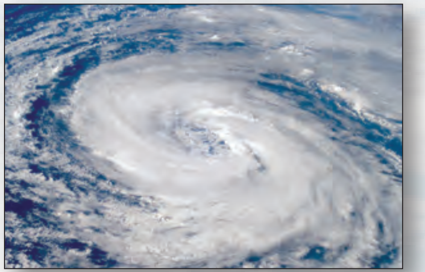


Table 3. Hurricanes that affected but did not make landfall (indirect hit) on North Carolina's Outer Banks, 1878–2004.

[Listed in descending order of wind speed; wind speed is approximate wind speed at closest approach to land. mph, miles per hour; Category, hurricane category on Saffir-Simpson Hurricane Scale]

Wind speed (mph)	Name	Year	Approximate location	Notes
			Category 3 hurricane	
124	None known	—	30 miles east of Hatteras	A Category 3 storm offshore; borderline hurricane winds on Hatteras.
120	Helene	1958	15 miles seaward of Cape Lookout	Produced hurricane winds on the Outer Banks, but no extensive damage.
115	Bob	1991	30 miles east of Cape Hatteras	Caused significant damage in the northeastern United States.
115	Emily	1993	20 miles seaward of Cape Hatteras	Produced hurricane winds on the Outer Banks.
101	Dennis	2005	About 70 miles southeast of Cape Lookout	Made landfall on Sept. 4 at Core Banks as a tropical storm, although it also had characteristics of a nontropical storm.
			Category 2 hurricane	
104	None known	—	15 miles east of Avon	Extensive beach erosion and flooding; drinking water in Hatteras contaminated. Five-minute sustained wind speeds of 80 miles per hour at Hatteras.
101	Great Atlantic Hurricane of 1944	1944	Just east of Cape Hatteras	Sand walls built by Civilian Conservation Corps in Avon acted as dikes, holding floodwater in the island interior.
98	Alex	2010	10 miles east of Cape Hatteras	Caused one death on the Outer Banks.
			Category 1 hurricane	
90	Ione	1955	Salter Path, North Carolina	Also crossed Outer Banks near Duck as a tropical storm when returning to sea.
81	Gladys	1966	Near Cape Hatteras	Produced hurricane gusts near Hatteras.
75	Ginger	1971	10 miles south of Cape Lookout	Tied with San Ciraco (1899) (see table 2) as longest-lasting hurricane.

Table 4. Historical hurricanes that affected North Carolina's Outer Banks, 1586–1846.

Year	Date	Approximate location	Notes
1586	June 13	Roanoke Island	Sir Francis Drake's fleet scattered; Drake brings unhappy Roanoke Islanders home.
1587	August	Roanoke Island	Sir Francis Drake's ship forced to cut anchor near Roanoke Island and put out to sea for 6 days.
1591	August	Roanoke Island	Severe storm with high wind.
1667	Sept. 6	North Outer Banks	Believed to have passed through the Outer Banks on its way to southern Virginia.
1669	Aug. 18	Northern Outer Banks	None.
1670	Aug. 6	Northern Outer Banks	None.
1749	Oct. 18–19	Unknown	Nine ships reported lost at Ocracoke.
1785	Sept. 23–24	Ocracoke	Many cattle apparently drowned.
1788	July 23–24	Near Cape Hatteras	Many sailing vessels demasted, driven ashore, or destroyed.
1795	Aug. 2	Hatteras/Ocracoke	Eighteen Spanish fleet vessels driven into Cape Hatteras shoals.
1806	Sept. 28	Coastal North Carolina	A large number of ships wrecked at Ocracoke Inlet.
1821	Sept. 2	Cape Lookout	Long Island Hurricane struck west of Ocracoke near mouth of Pamlico Sound.
1825	June 3–4	Coastal North Carolina	More than 20 vessels driven ashore at Ocracoke.
1827	Aug. 24	Hatteras	Diamond Shoals light ship swept off anchor.
1830	Aug. 2	Between Capes Hatteras and Lookout	Wind records for this storm do not provide conclusive information.
1837	October	Outer Banks	Racer's Storm made initial landfall on Yucatan Peninsula. At least three ships and 90 lives lost near the Outer Banks.
1839	Aug. 28–30	Offshore of Cape Hatteras	Twelve vessels damaged at Ocracoke.
1842	July 12	Portsmouth	Believed to be one of the most severe storms in Outer Banks history. Homes swept away and livestock drowned.
1842	Aug. 24	Ocracoke	Three ships (*Congress*, *Pioneer*, and *Kilgore*) lost off the Outer Banks.
1846	Sept. 7	Hatteras	Slow-moving storm created Oregon and Hatteras Inlets.

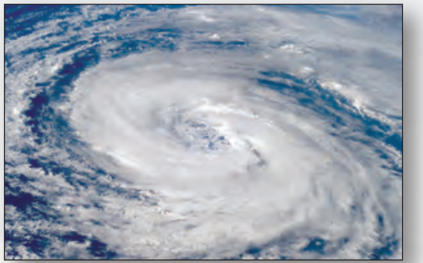
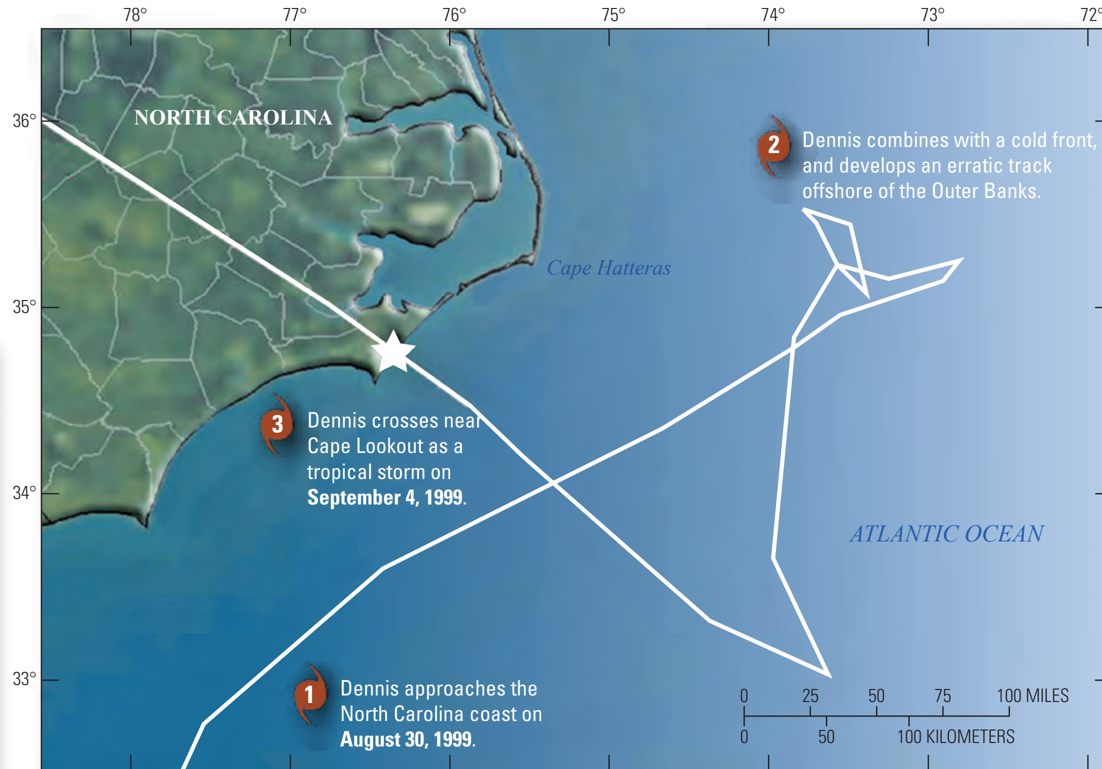


Figure 17 (right). Path of Hurricane Dennis (white line) as it approached and made landfall on the coast of North Carolina in 1999. *Background image courtesy of the State Climate Office of North Carolina.*

Figure 18 (above). Exhibiting characteristics typical of both tropical and extratropical storms, Hurricane Dennis caused high waves and flooding on the Outer Banks in August and September 1999. Kitty Hawk appears in this photograph. *Photograph by Carl Miller, courtesy of the U.S. Army Corps of Engineers.*



Hurricane Dennis: August 1999.—Hurricanes tend to pass through an area relatively quickly and, therefore, the relatively short duration of high winds limits wave size. In August 1999, Hurricane Dennis was an exception to this rule when it followed an erratic course off the North Carolina coast (fig. 17) and generated disproportionately large waves for its size.

Dennis began as an unusual asymmetric tropical storm with a wide, loose eye. As it tracked northeast off the North Carolina coast, Dennis weakened after merging with a cold front, and it began to take on characteristics of both a tropical cyclone and a subtropical or extratropical cyclone (Beven, 2000). It moved in a zigzag pattern off the North Carolina coast from August 30 until September 4, 1999 and finally made landfall near Cape Lookout as a tropical storm on September 5.

Because Dennis had characteristics of both a northeast storm and a hurricane, effects of the storm were surprisingly intense. Significant wave height reached more than 7 m (23 ft) (measured at the Field Research Facility Waverider buoy in 18 m (59 ft) water depth); those waves caused extensive island flooding (figs. 18, 19). Although Dennis was not a hurricane on the Saffir-Simpson scale at landfall, it ranked as a class 4 storm on the Dolan-Davis scale for northeast storms (see the later section Northeast Storms).

Hurricane Isabel: September 18, 2003.— On September 11, 2003, Hurricane Isabel tracked westward in the central Atlantic as an intense Category 5 hurricane. One week later, on September 18, when Isabel made landfall near Drum Inlet on Core Banks, its intensity had decreased to Category 2. Even so, State and Federal governments approved $155.2 million in assistance to meet North Carolina damage claims (Federal Emergency Management Agency, 2003), and the National Hurricane Center estimated actual property damage at about $340 million (fig. 19).

Isabel cut two inlets through Hatteras Island, one each north and south of Hatteras Village. The north breach destroyed a section of North Carolina Highway 12, thus isolating Hatteras Village's 300 residents (fig. 20). The U.S. Army Corps of Engineers sealed the breach 44 days after it opened with sand dredged from the federally maintained ferry channel between Hatteras and Ocracoke Islands (figs. 21, 22) (Wutkowski, 2004). Final cost estimates for closing the breach, excluding road and utilities reconstruction, were $6.5 million.

In addition to breaching Hatteras Island, Hurricane Isabel destroyed several oceanfront houses and Jennette's fishing pier in Nags Head (fig. 23), caused extensive road damage, and left standing water in the interior of the island (fig. 24). On September 18, 2003, Isabel generated a 12.1 m (39.7 ft) wave, the largest recorded at the Field Research Facility in Duck, NC, since it began operation in 1977.

Figure 19. Damage from Hurricane Isabel at Kitty Hawk, North Carolina on September 19, 2003. *Photograph by William Birkemeier, courtesy of the U.S. Army Corps of Engineers.*

Figure 20. Hatteras Village and the north breach caused by Hurricane Isabel in September 2003. *Photograph by Michael Halminski.*

Figure 21. U.S. Army Corps of Engineers crews worked around the clock at Hatteras Village to close the inlet opened by Hurricane Isabel. The cost of closing the inlet, excluding road and utilities reconstruction, was $6.5 million. *Photograph by Michael Halminski, October 20, 2003.*

Figure 22. The inlet cut by Hurricane Isabel remained sealed, as shown in this photograph taken in April 2007. Fresh sand in flood tidal delta created valuable new habitat. *Photograph by J.J. Smith.*

Figure 23. Jennette's fishing pier in Nags Head, North Carolina, before (***A***) and after (***B***) Hurricane Isabel (both photographs from September 2003). ***A****, photograph by Robert Dolan;* ***B****, photograph by Andrew S. Coburn, courtesy of the Duke University Program for the Study of Developed Shorelines.*


A
B

Figure 24 (page 34 and 35). Kitty Hawk, North Carolina, September 2003. ***A***, Maintained dune line between house and road. Two days before Hurricane Isabel made landfall, storm waves encroached on the house pilings. Following the storm, the house (***B***) survived the storm, although the road immediately behind it (***C***) did not. ***A**, photograph by Robert Dolan; **B**, photograph courtesy of the U.S. Army Corps of Engineers; **C**, photograph courtesy of Duke University Program for the Study of Developed Shoreline.*

Northeast Storms

Extratropical northeast storms, (northeasters or "nor'easters"), are less studied and less well understood than hurricanes, but they cause greater changes on the barrier islands because they are much broader in extent, more frequent, and have longer durations (Dolan and Davis, 1992). Unlike hurricanes, which form over the warm tropical waters of the Caribbean and North Atlantic, northeast storms develop in the midlatitudes along weather fronts that separate cold, dry polar air from warm, moist tropical air. Their name comes from the northeasterly winds that predominate as they move along the Middle Atlantic coast.

Whereas consequences of a hurricane can be felt well inland, for the most part the effects of northeast storm are limited to coastal areas. The likelihood of a hurricane strike at a specific place and time is relatively small, and hurricanes generally move through an area in a matter of hours. A persistent northeast storm, however, may batter coastal areas for several days, causing the coastline to respond and adjust to the storm's conditions (fig. 25). Northeast storms affect the coast of North Carolina each year with durations that range from a few hours to several days. A storm in October 1994 lasted for nearly 10 days—the longest duration of any storm (persistent waves higher than 1.5 m) between 1985 and 2004.

Like all storms, northeast storms arise in areas where the atmosphere is unstable and, by forming, they reduce or eliminate these instabilities. Northeast storms also require support from the jet stream to form and, therefore, their prevalence is closely related to seasonal changes in the jet stream's position and strength. The primary northeast-storm season is October through April.

Figure 25. The Nags Head Chief of Police inspects collapsed remains of a cottage in South Nags Head after a northeast storm produced high waves for three days in April 1987. *Photograph by Drew C. Wilson, courtesy of the Outer Banks History Center, Manteo, North Carolina.*

The Dolan-Davis Intensity Scale for Northeast Storms.— Understanding the influence of northeast storm characteristics on waves is critical to determining the effect of an individual storm on a shoreline. The Dolan-Davis Intensity Scale classifies northeast storms by multiplying the square of the significant wave height by the storm's duration (table 5). The result is a "power index" ranking from class 1 (weak) to class 5 (extreme). By using this scale, in conjunction with the record of wave duration and intensity on the Outer Banks from 1985 to 2004, it is possible to predict the recurrence, or return, interval of northeast storms of specific magnitude. Doing so indicates that a class 4 northeast storm can be expected about once every 10 years on the Outer Banks. This assessment depends on relative stability in climate throughout the return period. If the world climate changes markedly, then the return period could change as well.

Table 5. Dolan-Davis Intensity Scale for Atlantic Coast northeast storms.

Class	Beach erosion	Dune erosion	Overwash	Property damage
1	Minor	None	None	None.
2	Moderate	Minor	None	None.
3	Extending across beach	Significant	None	Moderate.
4	Severe with recession	Severe or localized destruction	On low-profile beaches	Loss of structures at community scale.
5	Extreme	Dunes destroyed over extensive areas	Massive, in sheets and channels	Extensive regional losses in millions of dollars.

The Ash Wednesday Storm.—General awareness of the potential force associated with northeast storms increased after the Ash Wednesday storm of March 5 to 8, 1962. This storm affected 1,000 km (622 mi) of the Atlantic Coast, caused $300 million in damage (1962 dollars), and generated open-ocean wave heights in excess of 10 m (33 ft). The center of the storm remained nearly stationary off the Mid-Atlantic coast for 3 days while an area of high pressure (anticyclone) over southeastern Canada blocked its northward progress. The Ash Wednesday storm was particularly devastating on the Outer Banks. Because it coincided with the highest monthly tides, increased storm surge and high waves extensively damaged infrastructure (fig. 26). However, it became clear after the storm that, even though undeveloped barrier islands change configuration in response to extreme storm conditions, they subsequently readjust in response to normal conditions (Dolan and others, 1973).

Halloween Nor'easter of 1991—The "Perfect Storm."— A storm defying conventional characterization pounded the Outer Banks for 5 days beginning on October 27, 1991. Like Hurricane Dennis in 1999, the Halloween or All Hallows' Eve northeast storm resulted from the interaction of both tropical and midlatitude systems. The bestselling book *The Perfect Storm* by Sebastian Junger was based on this event.

Three separate weather systems combined to create the Halloween storm: a cold front moving southward from Canada, Hurricane Grace located in the central Atlantic Ocean, and an extratropical low-pressure system generated in the central United States on October 26, 1991 (Dolan and Davis, 1992). The Canadian front moved southward, changing the path of Hurricane Grace, while the extratropical low tracked northeast toward the other two systems. When the extratropical low-pressure system encountered the moisture and strength of Hurricane Grace, it intensified substantially and stalled. It eventually absorbed Grace and began tracking westward toward the New England coast.

When combined, the three weather systems produced almost 1,680 km (1,044 mi; 1,200 knots) of continuous fetch from Newfoundland to Florida that persisted for days. Storm surges ranged from 1.5 m (5 ft) in Massachusetts, where storm effects were worst, to 0.6 m (2 ft) on the Outer Banks. The storm caused $2.2 million in damages to North Carolina, and 76 buildings were condemned in Dare County (which includes the Outer Banks) alone.

Its exceptionally long fetch was one reason the Halloween storm generated the largest maximum wave heights of any northeast storm between 1942 and 2004. Field Research Facility instruments at Duck, NC, measured a significant wave height of 5.9 m (19.3 ft) in 18 m (59 ft) water depth. An estimated deep-water wave height of 10.7 m (35 ft), calculated after the storm, is the highest of any poststorm estimated wave height on record (Dolan and Davis, 1992).

Another large storm battered the Outer Banks just a few days later on November 8, 1991 and generated waves 4.9 m (16 ft) high. Structures already weakened in the Halloween storm were additionally damaged as a result.

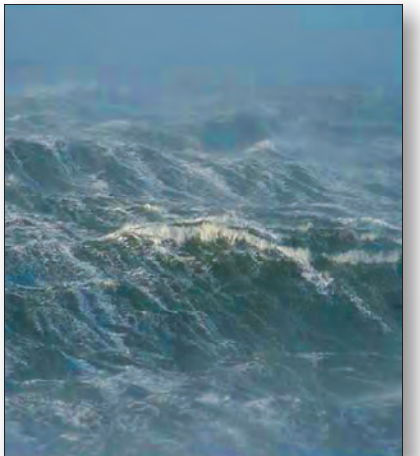


Figure 26. The Ash Wednesday Storm, March 1962, was one of the most powerful northeast storms on the Outer Banks. *Photograph courtesy of the Outer Banks History Center, Manteo, North Carolina.*

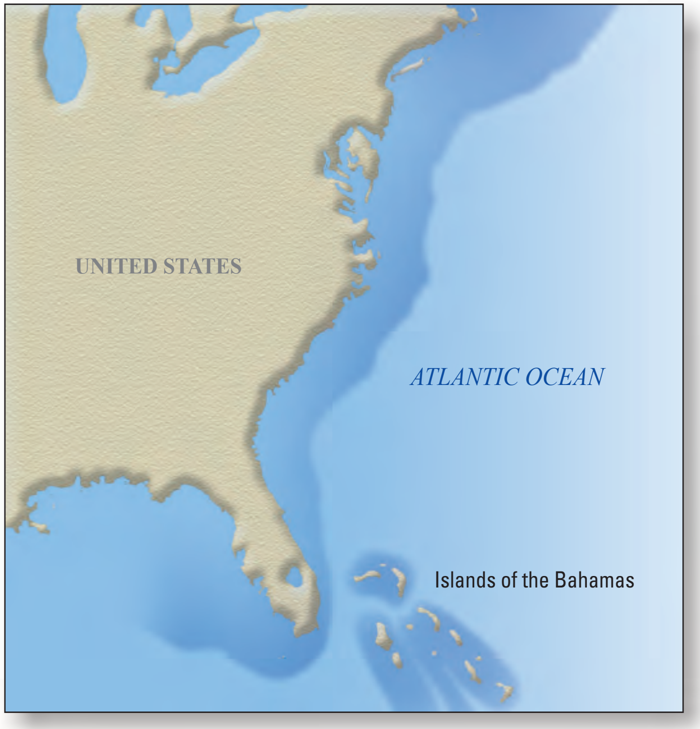


Figure 27. Approximate location of Atlantic coastlines of the United States and the Bahamas (seaward edge of darker blue shading) 15,000 years ago, when sea level was approximately 100 meters (330 feet) lower than it is today.

Sea-Level Change

Sea level varies markedly at millennial time scales. Since the last glacial maximum, about 20,000 years ago, sea level has risen nearly 120 m (400 ft) as air temperatures warmed and glaciers and ice sheets melted. Notably, such large changes in glacial extent and in sea level appear to be a common thread in Earth history. Glaciers have advanced and retreated many times during the last billion years, and each change caused an associated fall or rise in sea level. More than 20 glacial advance-retreat cycles and sea level fall-rise cycles are recorded during the Pleistocene—the past 2 million years—alone (Menzies, 2002). From a geological perspective, the current climate represents a relatively short warm period of rising sea level between much longer glacial advances associated with falling sea levels.

In recent years, highly publicized concerns about human-induced climate warming have generated public interest in sea-level rise. Observations indicate that global sea level rose about 17 centimeters (cm) (6.7 inches (in.)) during the 20th century, an average rate of 1.7±0.5 millimeters per year (Bindoff and others, 2007). Estimates of what may happen in the future vary considerably.

Regardless of the accuracy of projections of the future rate of change, sea level has been rising slowly for thousands of years. Even without human-induced climate change, governments around the world will inevitably have to adapt to ocean encroachment on low-lying coastal cities and island communities. Because the slope and elevation of the land on the Outer Banks are generally low, a small vertical change in sea level can translate into a relatively large horizontal change in the location of the coastline. In their natural state, the sandy islands move and adapt to many changes in the physical environment. During the cooler glacial periods, when water was withdrawn from the seas and stored as glacial ice, the shorelines moved seaward (fig. 27). As the coastline is engineered or “hardened,” the islands’ ability to respond to such environmental changes diminishes.

Dominant Sedimentary Processes

Sediment on the Outer Banks moves primarily in four ways: longshore transport, inlet dynamics, overwash, and eolian transport. These four methods transport sediment along the beach in the nearshore area by moving sediment through breaks in the island and by carrying sand across the island through wind and wave action. Each of these processes is discussed below.

Longshore Sediment Transport

Longshore sediment transport moves sediment along the coast in response to waves that approach the shore at an angle and then break. These waves move water and sediment shoreward at an angle to the shoreline, and then wave backwash rushes directly back into the ocean (perpendicular to the shoreline), generating a net motion in the direction of the wave angle. The longshore current can carry tons of sediment, suspended sea creatures (such as jellyfish), and other objects along the coast. Littoral drift is the movement of sediment and other objects by longshore currents. Although longshore currents change direction periodically, they usually have a net flow in one direction in any given location. Along the Outer Banks, sediment drifts southward toward Cape Hatteras and Cape Lookout.

Inlet Dynamics

Inlet dynamics, the complex interactions at inlets, are one of the two main processes that transport sediment across the barrier-island shore. Sediment is transported principally by flowing through existing inlets or through newly formed ones.

When high waves and intense storms cut through a barrier island, they create an inlet and transport large amounts of saltwater and sediment landward across the island (Moslow and Heron, 1979). Once an inlet opens, water and sediment carried by storms and littoral drift begin flowing through. Most Outer Banks inlets are temporary; in a few years or decades they clog with sand transported by longshore currents. Sometimes, however, water flowing in and out is forceful enough to keep the inlet open.

Inlets may form from the ocean side to the bay or, conversely, from the bay side to the ocean. Both cases result from storm-induced high wave energy and water levels. If the inlet initiates on the ocean side, storm surges and high waves drive seawater across the island and into the bay. Storm-pushed seawater flows across the island into areas of progressively lower topography, and channels form and may erode to depths that permit water flow in both directions. Inlets that form from the bay side provide return capacity for excess water in the bay. Storm surge and overwash may raise water level on the bay so high that existing inlets do not provide enough return capacity during ebb tides. Then, the excess bay water may find a path of least resistance across the island and form an "outlet."

Once an inlet is established, it becomes one of the most important features shaping the island because it interrupts littoral drift (Bodge, 1993). The landward transfer of sediment through inlets may account for as much as half of sand lost from the littoral drift system (Pierce, 1969). The energy in waves and tides pushing sediment through the inlet from the ocean side is greater than the energy in ebb tides pushing back out from the bay side. Much of the sand lost from the ocean side accumulates underwater on the sound side of an inlet and forms a flood tidal delta (fig. 28).

Sedimentary deposits filling closed inlets compose as much as 25 percent of the barrier island, a percentage that varies with the number and duration of inlets on a particular island. Inlet fill material may make up 14 to 16 percent of the most recent, or Holocene, sediments on Core Banks (Moslow and Heron, 1979). Inlets also affect the island's ecology (Godfrey, 1970). Along with sediment, water flowing through the inlet carries organisms that colonize the emerging flood tidal delta with marsh grasses once the inlet closes.

Human cultural history on the Outer Banks is also linked to inlets (Dunbar, 1958). More than 30 inlets have opened and closed since the first settlers arrived more than 400 years ago (fig. 29). During the past 125 years only Ocracoke, Hatteras, and Oregon inlets remained open to serve as waterways leading to the bays and sounds; two of these, Hatteras and Oregon, formed during the same storm in 1846. Because local populations depend on inlets, they are commonly dredged to maintain navigation channels between the sound and the ocean.

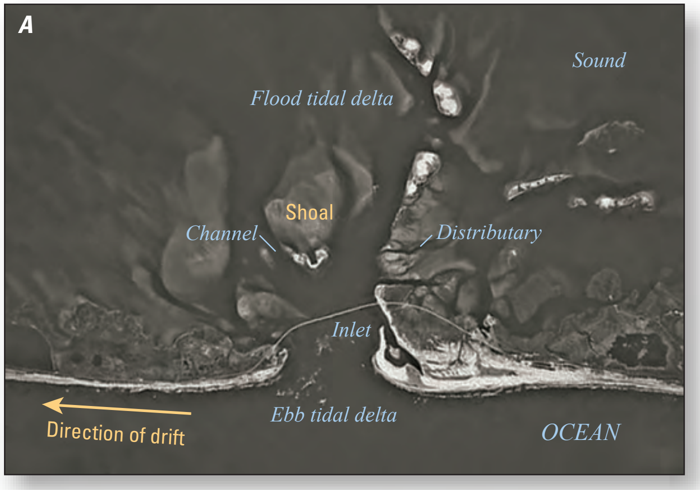
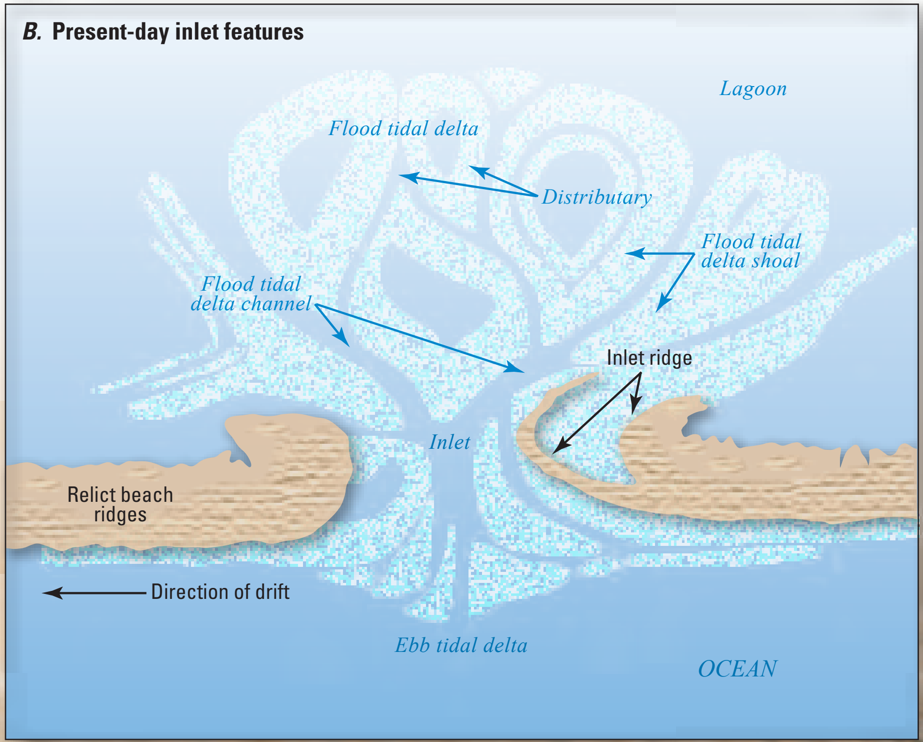
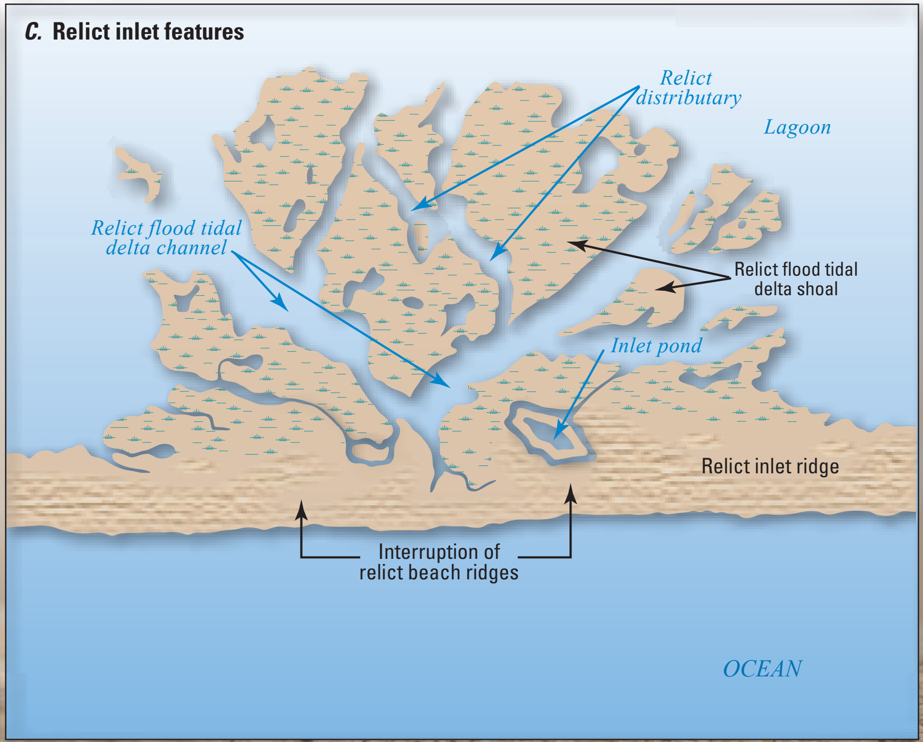


Figure 28 (page 42 and 43). Elements of inlets and associated sedimentation processes: ***A***, features of Swash Inlet (Core Banks, North Carolina) in 1941. *Photograph courtesy of the National Park Service*; ***B***, simplified drawing of present-day inlet features; ***C***, simplified drawing of relict inlet features *(both drawings after Fisher, 1962); **D***, relict inlet features on the Outer Banks. *Photograph by Kevin Adams.*





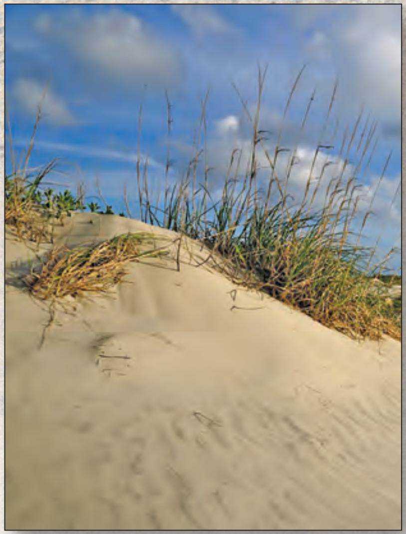
Overwash

Less intense hurricane or northeast-storm waves can be the agent of the second main process, overwash, that moves sand across the island. During a storm, a barrier island's sandy beach changes shape in response to the high wind and waves, and the beach face flattens as it dissipates increased wave energy. Wave runup may extend beyond (inland of) the first dunes into areas that normally receive wind-blown deposits. The water and sediment penetration is called overwash, and the resultant deposits are known as a washover fan (fig. 30). Very large or repeated overwash events may result in a larger deposit area, known as a washover flat.

Washover sediments may initially kill the underlying plant life now blanketed with sand, but the vegetation of the back barrier is resilient. Marsh grasses will sprout through overwash fans in a matter of weeks or months, and they may grow from plant fragments "dispersed in the storm surge-leveled sand" (Snyder and Boss, 2002). A particularly thick layer that covers and destroys the existing plant life usually is recolonized in less than a year (Davis, 1997). Overwash may limit ecological succession, because woody plants are not tolerant of frequent seawater flooding or sand burial.

Figure 29. Inlets of the Outer Banks of North Carolina. Blue type, relic (historical) inlets; red type, current inlets. Some inlets opened and closed more than once during the indicated time periods *(after Stick, 1959; Fisher, 1962).*

Figure 30. Storm surge near Cape Hatteras in 1973. ***A***, Overwash breached the barrier dune and flooded buildings behind it. ***B***, The same location one year later, showing a washover fan produced by sediment carried in with floodwaters and indentation of the shoreline, characteristic features at overwash sites. *Photographs by Robert Dolan.*



Wind Transport

Wind (eolian) transport redistributes sediment. Inland of the beach, all natural Mid-Atlantic coast barrier islands have dunes of various sizes created by wind-blown sand. Wind of about 25 to 30 km/h (15 to 20 mph) or faster can pick up and carry fine sand and deposit it anywhere on the island. As with waves, stronger winds can carry both more and larger sand grains. Large dunes may form in areas with wide, active beaches and powerful prevailing winds.

The largest and oldest dunes on the Outer Banks are 3,000 to 4,000 years old (Fisher, 1962; Mallinson and others, 2008). As the islands formed, alternating periods of erosion and accretion resulted in the development of large fields of parallel dune ridges separated by depressions or swales. Vegetation invaded the dunes; the root structure held the sand in place while decaying plant matter covered the surface. Eventually, wind could no longer mobilize the sand, and maritime forests of oak and pine grew on the dune ridges. Nags Head Woods, Colington Island, and Buxton contain examples of dune ridges covered by maritime forests (fig. 31).

When maritime dunes are breached or destroyed, the sand can again be redistributed by wind, perhaps in new and differently shaped dune fields. Jockey's Ridge in Nags Head (figs. 32, 33) is a dune field created by sand redistributed from formerly stabilized ridges (Dolan and Runyan, 2001). Formed approximately 1,000 years ago, Jockey's Ridge is the largest active dune field on the Atlantic Coast.

Because of the beauty and unique features of Jockey's Ridge, in 1975 the State of North Carolina created a state park around it. By 1998, the park was hosting 900,000 tourists each year. Managing the large and dynamic dunes has been challenging. The elevation of the highest dune decreased from 42 m (138 ft) in 1953 to 22 m (72 ft) in 2004, and the dune's slow migration to the southeast encroaches on nearby homeowners. In 1994, approximately 13,700 cubic meters (m^3) (15,000 cubic yards (yd^3) was removed and relocated from the park's southern boundary to its northern boundary. In 2003, "almost ten times more sand, 125,000 m^3 (164,000 yd^3) was removed and placed on the northwestern side of the dune field to serve as a sand source area" (Mitasova and others, 2005).

The high frontal dunes evident today along much of the northern Outer Banks are not the result of wind transport. They are primarily the result of man's earlier efforts to restrict sand movement along the islands (Dolan, Godfrey, and Odum, 1973). For more information about these dunes, see the section Engineering the Outer Banks in Part II of this report.

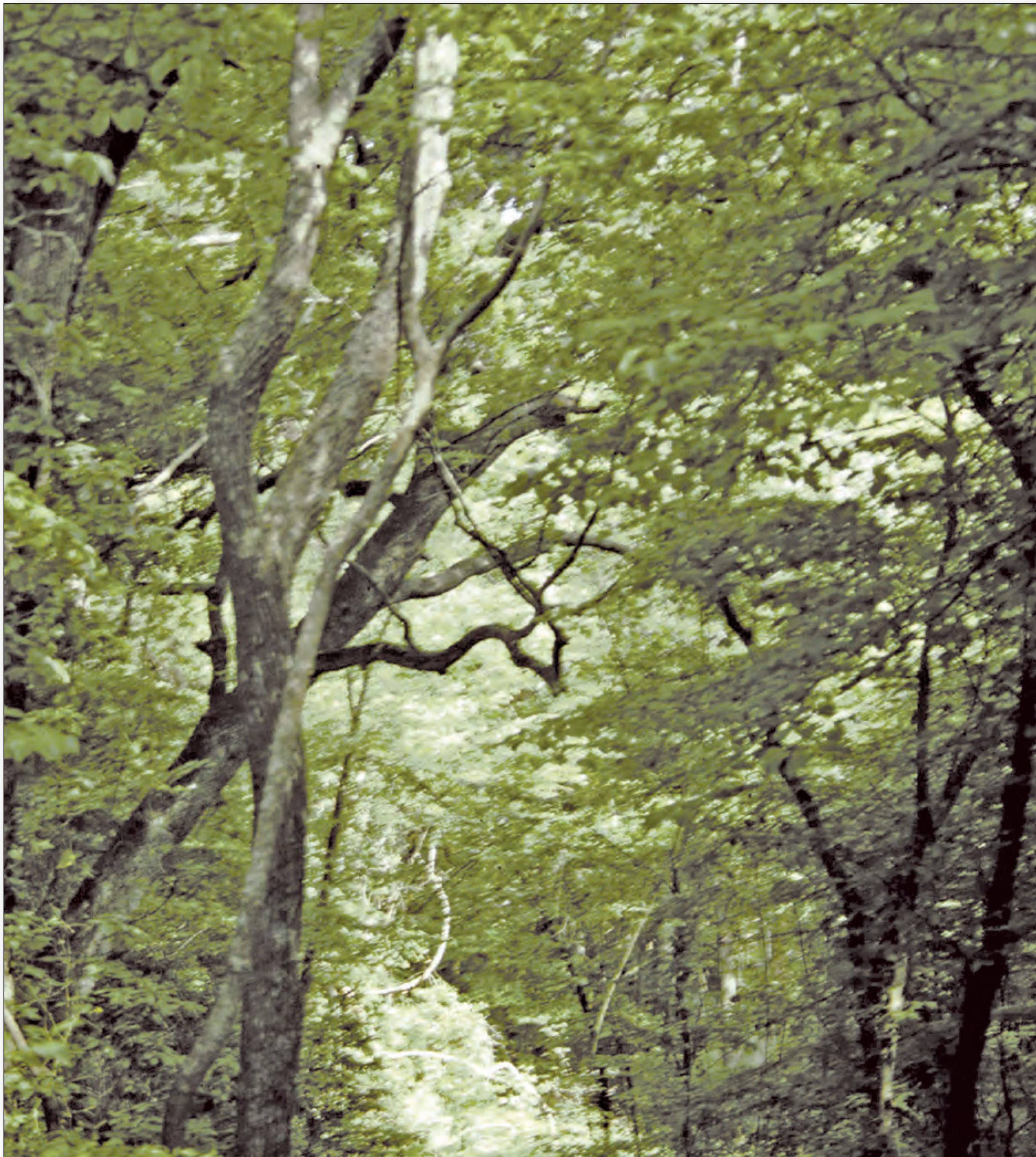


Figure 31. Maritime forest, Nags Head woods. *Photograph courtesy of The Nature Conservancy.*

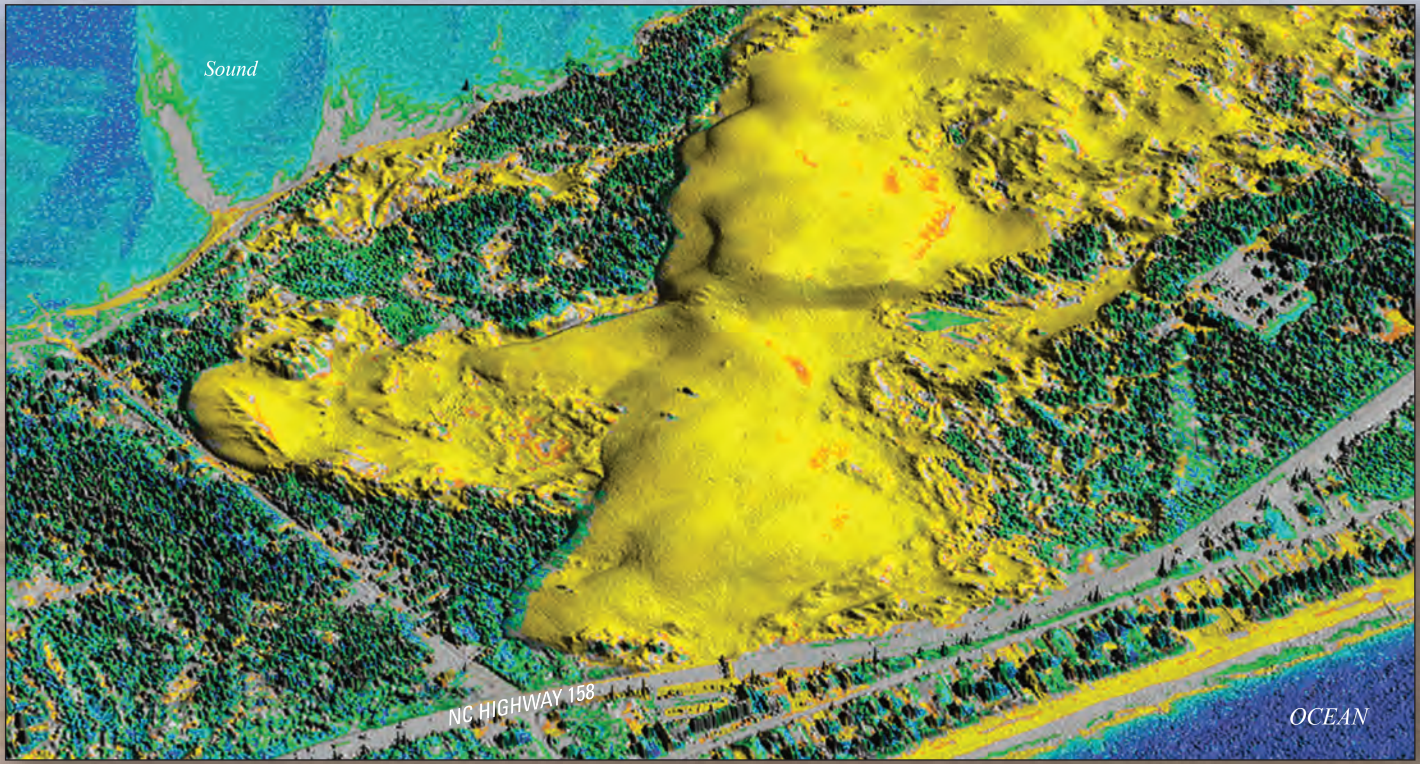


Figure 33. Image of Jockey's Ridge based on 1999 lidar (light detection and ranging). *Data produced by the U.S. Geological Survey, National Oceanic and Atmospheric Administration, and National Aeronautics and Space Administration (base image courtesy of Helena Mitasova).*

Figure 32 (facing page). The highest dune on the United States Atlantic Coast is Jockey's Ridge (Jockey's Ridge State Park, Nags Head, North Carolina). *Photograph by Kevin Adams.*

Geological History of Barrier Island Formation

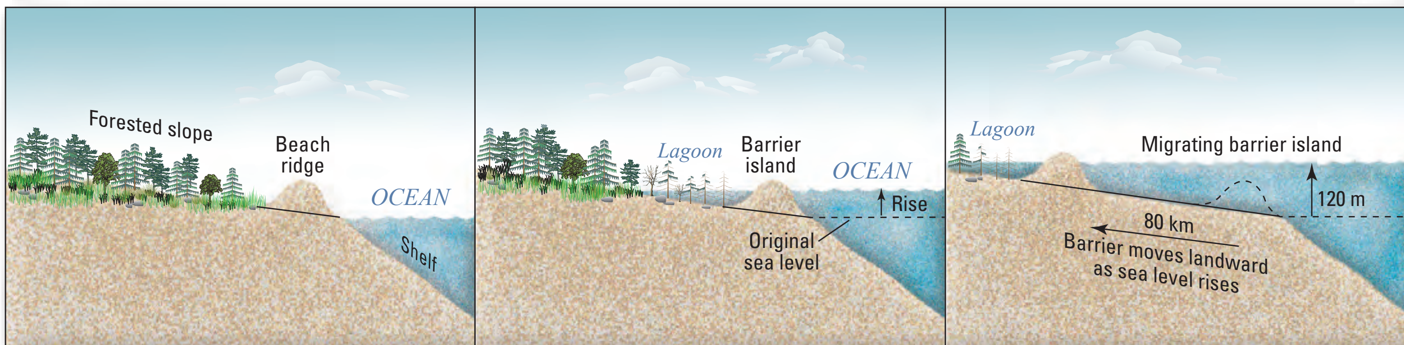
*. . . **I am strongly induced to believe that, as in music, the person who understands every note will, if he also possesses the proper taste, more thoroughly enjoy the whole, so he who examines each part of a fine view, may also comprehend the full and combined effect.***

—Charles Darwin (1831-1836), 1947, The Voyage of the Beagle

For many years Earth scientists have debated the processes responsible for forming barrier islands. Generally, the Outer Banks are believed to have formed from spit growth combined with beach emergence. Changes on sedimentary coasts are related directly to the geological origin of barrier islands, such as the amount and attributes of sediment, the magnitude of natural processes, and the stability of sea level.

The origin of the Atlantic Coast barrier islands is closely linked with the Wisconsin glacial episode in the Northern Hemisphere that began about 110,000 years ago. The great continental glaciers that formed in central Canada and northern Europe accumulated relatively rapidly, and they ultimately built glacial ice that covered most of present Canada and Western Europe. Water originating primarily from the ocean basins produced these great ice masses, and as a result global sea level fell by about 120 m (400 ft). At that time, the North Carolina shoreline was on the continental shelf 80 to 120 km (50 to 75 mi) seaward of its present position (fig. 27) (Emery, 1968).

Beginning 14,000 to 18,000 years ago, changes in the planetary heat budget triggered melting of Northern Hemisphere glaciers, and by 4,000 years ago sea level off North Carolina was close to its present position (Horton and others, 2009). The change from glacial to interglacial conditions marked the transition from the Pleistocene Epoch to the current Holocene Epoch and initiated the Holocene marine transgression (fig. 34). During this transgression, rising sea level advanced landward and drowned areas of the continental shelf that had been exposed during the Pleistocene.



A. 20,000 years ago, sea level was 120 m (400 ft) below its present level and 80 km (50 mi) seaward of its present position. Wind waves formed beach ridges (dunes) along the shelf.

B. Sea level rises and breaks through the dune ridge, flooding the low area behind the dune to form a lagoon or sound. The former dune line is now isolated as an island.

C. The island arrives at its present position in response to continued sea level rise. The island may contine moving landward if the slope behind it is low and sea level rise does not accelerate significantly.

Figure 34. The Holocene marine transgression and barrier island evolution *(after Hoyt, 1967). (Symbols courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).*

The barrier islands now rimming the Atlantic and Gulf coasts formed during the Holocene marine transgression. Three specific conditions allowed the islands to form (Dolan, 1996):

- A pause in the rapid rise of sea level
- Surplus sand that could be transported by waves, winds, and currents
- Storms that transported and deposited sand at higher elevations than were possible by normal tide ranges. As sea level slowly rose and the shoreline moved across the continental shelf, large masses of beach sand were moved with the migrating shore zone (Emery, 1968; Duane and others, 1972; Field and Duane, 1976). In addition, waves reworked sediment deposited as deltas within the coastal river systems, which then moved that reworked sediment along the shore. As time passed, the complex, elongated landscape of the Outer Banks evolved (fig. 35).

After sea-level rise slowed about 8,000 years ago, waves, currents, and winds reworked the sand to form the beaches and barrier islands that stretch from New England to Texas. The beaches continued to build seaward as long as the inshore system contained surplus sediment. Some parts of the Outer Banks may have been wider at that time, perhaps by 1.6 km (1 mi) or more. In narrow areas, inlets breached the islands and later filled in. Long spits connected the wider and more stable sections, such as the land areas near Cape Hatteras, Southern Shores, Colington, Nags Head Woods, Avon, Frisco, and Ocracoke, where sequences of beach ridges developed (fig. 36). In this way, long chains of Holocene barrier islands evolved.

Overwash and inlet processes (described previously) are also the primary agents of landward movement on the islands. During severe storms, high water and waves overtop the seaward dunes. As the sediment-laden water spills across the beach and flows toward the bays, a layer of sediment is removed from the beach and added to the island's interior. Overwash is more common along the low, narrow, microtidal Outer Banks than on some islands with larger dunes or cliffs of glacial till (Godfrey, 1976). The overwash process transforms the shape and position of the island but conserves much of the sediment mass.

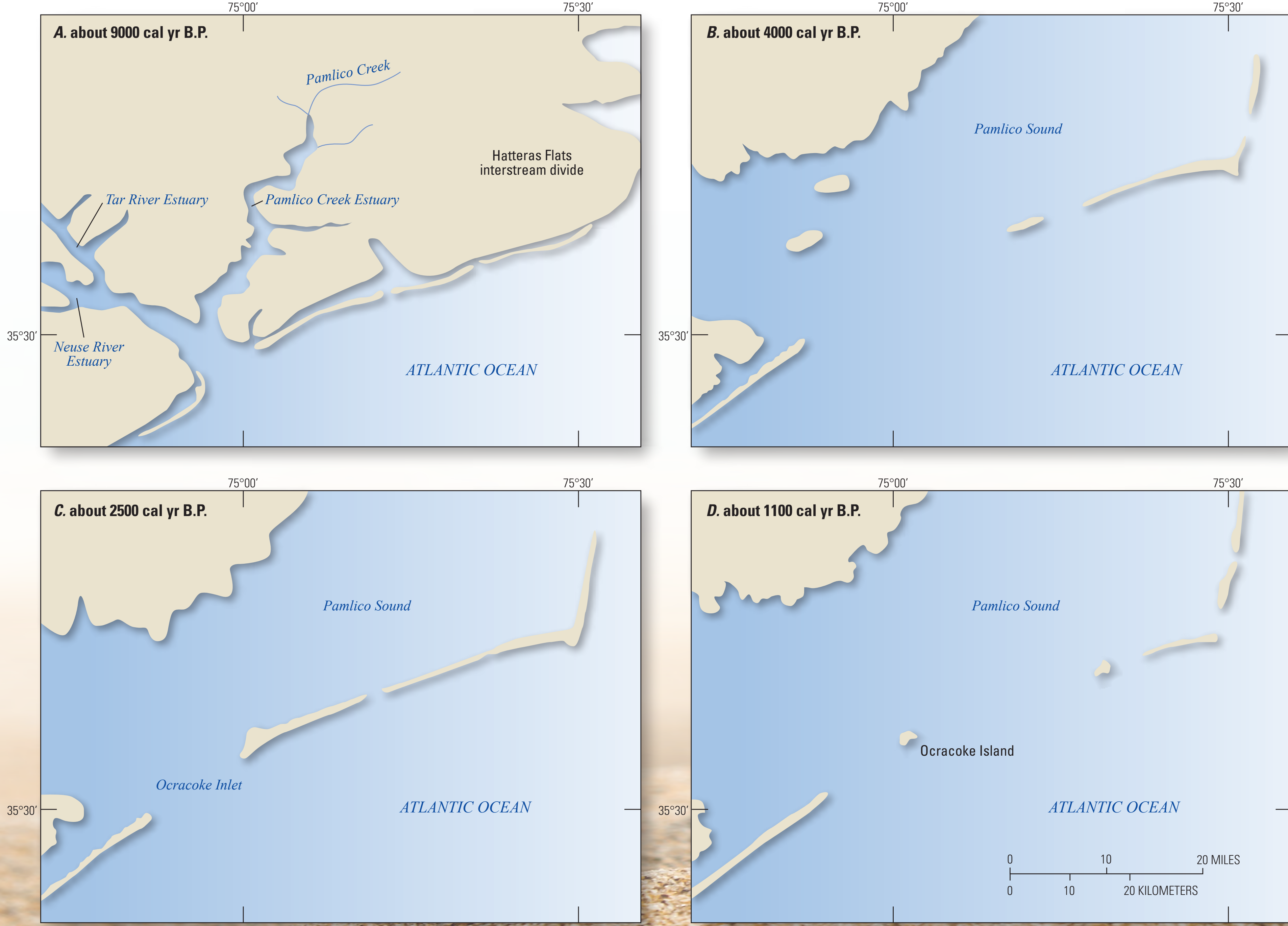

75°00′
75°30′
35°30′
A. about 9000 cal yr B.P.
Pamlico Creek
Hatteras Flats
interstream divide
Tar River Estuary
Pamlico Creek Estuary
Neuse River
Estuary
ATLANTIC OCEAN
B. about 4000 cal yr B.P.
Pamlico Sound
ATLANTIC OCEAN
C. about 2500 cal yr B.P.
Pamlico Sound
Ocracoke Inlet
ATLANTIC OCEAN
D. about 1100 cal yr B.P.
Pamlico Sound
Ocracoke Island
ATLANTIC OCEAN
0 10 20 MILES
0 10 20 KILOMETERS

Figure 35 (facing page). Paleoenvironmental reconstructions of the southern Pamlico Basin at four times during the Holocene. ***A***, About 9000 calendar years before the present (cal yr B.P.), sea-level rise flooded fluvial paleovalleys and produced narrow estuaries. The Hatteras Flats interstream divide separated Pamlico Creek from the Atlantic Ocean. ***B***, About 4000 cal yr B.P., destruction of an extensive section of barrier islands allowed normal-salinity waters, derived from northward migrating Gulf Stream eddies, to be carried into the southern Pamlico Basin in response to wind forcing. ***C***, By about 2500 cal yr B.P., barrier islands have formed again, and almost the entire Pamlico Sound had estuarine conditions. ***D***, About 1100 cal yr B.P., destruction of barrier islands along the southern Outer Banks resulted in a shallow, submarine sand shoal over which normal marine waters were carried. The Cape Hatteras region contained several inlets with large floodtide deltas. *(McDowell and others, 2009;* ***D*** *modified from Culver and others, 2007). (Entire figure modified from Grand Pre and others, 2011, and used with permission.)*

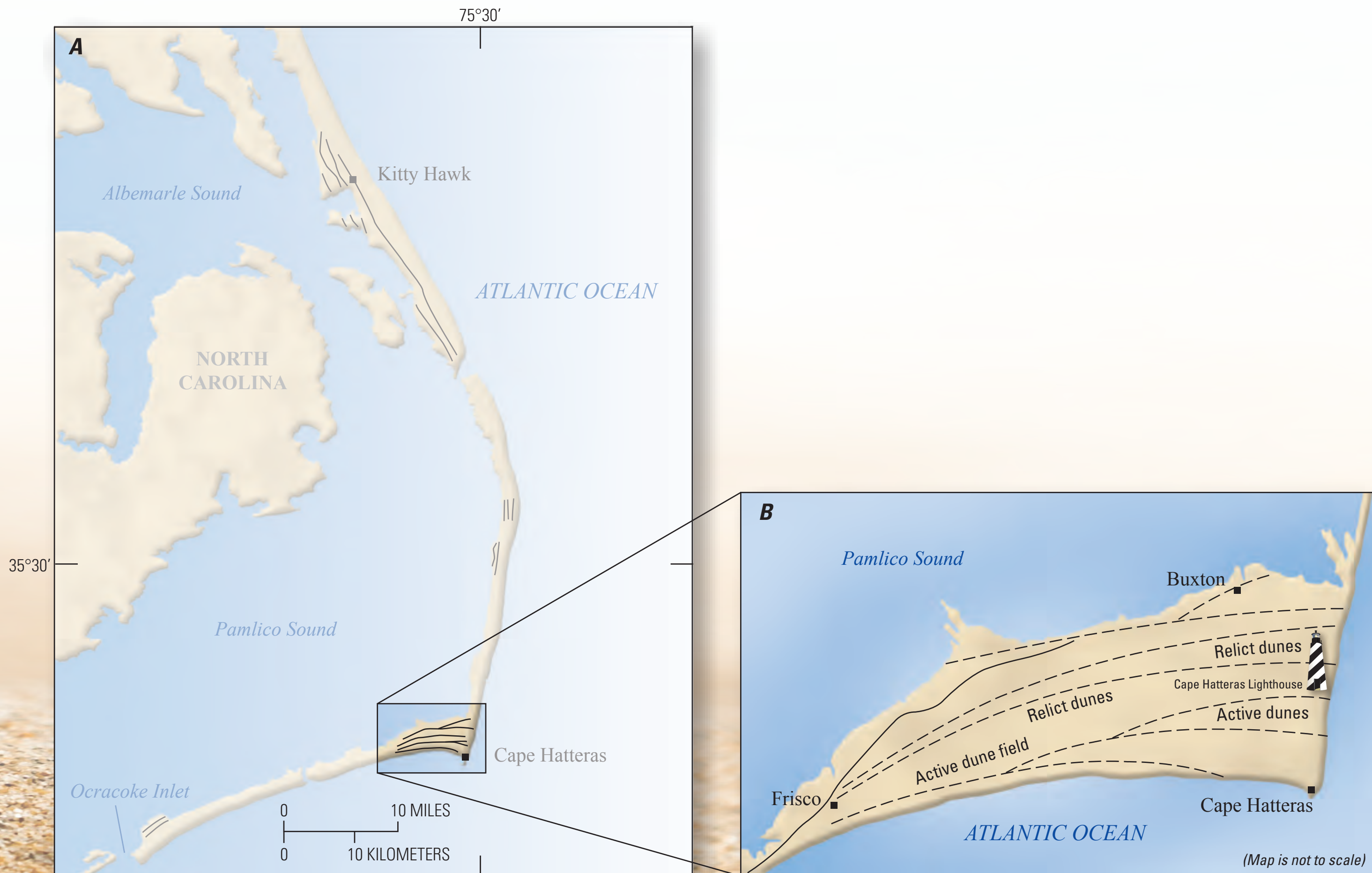


Figure 36. ***A***, Approximate distribution of high dune ridges of early Holocene age. ***B***, Complex pattern of dune ridges at Cape Hatteras. *(After work by Fisher, 1962.) (Symbols courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).*

Beach Configuration and Beach Erosion

Shoreline Configuration

Age by age, the sea here gives battle to the land; age by age, the earth struggles for her own, calling to her defense her energies and her creations, bidding her plants steal down upon the beach, and holding the frontier sands in a net of grass and roots which the storms wash free.

—Henry Beston, 1928, The Outermost House: A Year of Life on the Great Beach of Cape Cod

Even a cursory inspection of high-altitude aerial photographs of the Atlantic Coast reveals an interesting crescentic pattern on the seaward-facing barrier island beaches (fig. 37). More than a natural curiosity, these landforms are products of complex interactions between waves, inshore currents, tides, and storm surge. Shore-zone processes naturally configure the wave-dominated sedimentary coastlines of the Outer Banks into repeating crescentic patterns, rather than straight forms. The larger-wavelength forms (more than 10 km (6.2 mi)) are less apparent during a stroll along the beach because their curvature is gentler and their relative amplitude is, therefore, smaller. In long sections of the coast, the absolute amplitude of a stretch of curved coastline is proportionately greater than the amplitude of smaller crescentic features (a more-detailed discussion follows).

The broad arcs of the North Carolina coast (the Carolina capes) compose the largest crescentic landforms, spanning 150 km (93 mi) or more. Smaller forms have developed within them, such as beach cusps (25 to 100 m (82 to 328 ft) long), giant beach cusps (100 to 500 m (328 to 1,640 ft) long), and some larger forms 1.5 km (0.9 mi) or more long (Dolan, Hayden, and Vincent, 1974). Inshore bars and troughs also assume crescentic and periodic configurations in response to sea states, tides, inshore currents, and changes in sea level (Sonu, 1973). Smaller forms appear, disappear, and migrate along the shoreline, whereas large ones establish the spatial distribution of shoreline erosion and storm overwash (fig. 38) (Dolan, 1971).

Similarly, analysis of overwash patterns and 40-year averages of shoreline positions suggests that periodicities also exist for long-term average shoreline erosion and the penetration of storm surge during a single storm. These patterns indicate the sites of erosion and storm damage. Although overwash and washover deposits were noted all along the Outer Banks following the Ash Wednesday storm of 1962, the distance that sand penetrated inland differed markedly from place to place (fig. 39).

Some 1950s homes on the Outer Banks have weathered hundreds of storms, including the great Ash Wednesday northeast storm. Other houses nearby have long since disappeared in response to beach erosion. The vulnerability of some places along the coast is not simply a matter of chance, but rather a function of location that the crescentic landform patterns influence. These patterns are common on sandy beach deposits, not unlike the wave-like deposits of wind-blown sand found on and around fields of dune sand. Research carried out along the Outer Banks suggests that at many scales, shore-zone processes and shore-zone landforms assume systematic patterns along and across the coast (Dolan and others, 1979a).

Figure 37. Large crescentic landforms of the Outer Banks. *Satellite image of December 26, 1999, courtesy of the SeaWiFS Project, National Aeronautics and Space Administration Goddard Space Flight Center, and ORBIMAGE, http://visibleearth.nasa.gov/.*

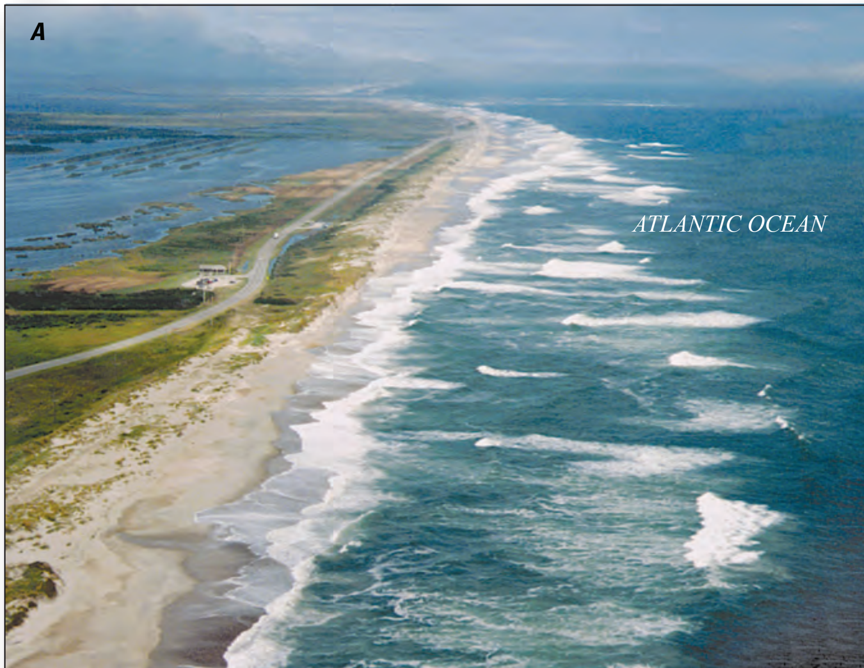


Figure 38 (left). Small crescentic landforms, which here appear as seaward-pointing tongues of sand, are low lobate hills; they originate, migrate, and dissipate along Outer Banks beaches. ***A***, Pea Island National Wildlife Refuge, looking north. *Photograph by Robert Dolan, September 2003.* ***B***, Cape Hatteras, looking south. *Photograph by J.J. Smith, April 1996.*

Figure 39 (above). Overwash (storm surge penetration) appears as bright white areas along Hatteras Island, 1962. *Photograph courtesy of the U.S. Army.*

Shoreline Erosion and Deposition

Erosion dominates most of the developed coasts of the United States. Shoreline-change data show that land losses exceed gains along 75 percent of the Atlantic Coast, 85 percent of the Gulf Coast, and 50 percent of the Pacific Coast (Dolan, Hayden, and Lins, 1980). Stratigraphic studies indicate that most Mid-Atlantic barrier islands are moving landward—which means that erosion dominates most of the coastlines in this region, too. Peat deposits, tree stumps, and remnants of forest stands, which generally form on the sound side of barrier islands, can be found on open ocean beaches (fig. 40) (Kraft and others, 1973; Dillon and Oldale, 1978; Field and others, 1979). This trend in erosion is attributed to a rise in sea level, a reduction in the supply of river sediment to the coast, human alteration of inshore processes, and changes in the frequency and magnitude of storms.

Although most of the Outer Banks are migrating landward (they are "transgressive"), about 20 percent of the islands are building into the ocean (prograding seaward) because of their specific geomorphic characteristics. In these areas, a definitive set of shore-parallel beach ridges can be seen where the beach builds outward, and these islands, such as at Cape Hatteras, are consequently wider than usual (Moslow and Heron, 1994) (fig. 36). Of the two general storm types that affect the Atlantic Coast of the United States, tropical hurricanes and extratropical northeast storms, hurricanes can be the more intense. Wave heights generated by hurricanes typically range from 5 to 10 m (16 to 33 ft), and powerful hurricanes can produce storm tides up to 5 m (16 ft). The two most likely landfall zones for hurricanes along the Atlantic Coast are south Florida and Cape Hatteras. Landfalls of Category 4 and 5 hurricanes on the Outer Banks are rare and average only about one per century

On the other hand, northeast storms cause most of the stormy weather, high waves, and storm surges leading to coastal erosion and property damage along the North Carolina coast. Northeast storms are more frequent, have longer durations, and strike much larger areas along the coast. Wave heights produced by northeast storms usually range from 2 to 5 m (6 to 16 ft), and although storm tides during northeast storms are generally lower, they can still exceed 2 m (6 ft). According to the 60-year record of northeast storms at Cape Hatteras, seven great storms were powerful enough to make prominent changes to the barrier island and beach landscapes. Two of these, the Ash Wednesday storm of 1962 and the Halloween storm of 1991, are designated “super nor’easters” in that they produced wave heights and storm tides equal to those of most hurricanes and left permanent scars on the barrier-island landscapes.

Any variation in water level or wave condition changes the position of the shoreline—the interface between land and water. Because winters along the Middle Atlantic coast are stormier than summers, the position of shoreline changes seasonally. The rise in sea level during past centuries has also contributed to the displacement of the shorelines landward. Despite the obvious nature of these relations, definitive prediction of the rate or magnitude of these displacements remains elusive. Coastal scientists and engineers have turned to empirical approaches by assembling datasets of historical shoreline positions and treating them as a time series.

Measurement of Coastal Change

Scientists analyze data about shoreline position in order to predict the rates at which shorelines will change. These data are obtained from various sources and have various degrees of accuracy. Sources include instrumented ground-level surveys, shoreline maps, navigation charts, aerial photography, and global positioning system (GPS), and light detection and ranging (lidar) data.

Instrumented surveys, or direct measurements, provide data of the highest accuracy and reliability, but detailed historical comparisons are lacking for most coastal areas. Because less than 5 percent of the United States’ coastline has been surveyed more than once, direct ground-level measurements are available only for a few scattered locations. Similarly, both GPS and lidar data have only recently become available. In contrast, maps, charts, and aerial photographs produced and distributed by the National Oceanic and Atmospheric Administration are available for most coastal locations and commonly date from the middle 1800s. Thus by using various sources of information, a shoreline’s position through time can be compiled into a single dataset. This dataset can then be used to produce a shoreline-change map that can in turn become the basis for new observations, measurements, and predictions about shoreline responses through time (fig. 41) (Shepard and Wanless, 1971; Dolan, Hayden, and others, 1979b; Miller and others, 2005; Morton and Miller, 2005).

The Outer Banks has an especially rich archive of mapping-quality aerial photography. The North Carolina coast was first photographed with mapping-quality aerial cameras after a severe hurricane in 1932 (Birkemeier and others, 1984). Since then, most of the barrier islands, capes, and inlets have been the object of numerous photographic flights. Areas at high risk from erosion or storm surge, such as the original Cape Hatteras Lighthouse site, have been photographed with mapping-quality cameras as many as 20 times during the past 50 years.

Figure 40. Remnants of a forest stand. As barrier islands migrate landward, such remnants may be exposed on ocean-facing beaches such as this one north of Rodanthe, North Carolina. *Photograph by Michael Halminski, autumn 1975.*

Management of Erosional Coasts

Coastal zone managers have made considerable progress instituting more stringent building standards in high-risk erosion areas. Structures are now elevated on pilings above most storm surge heights, and improved construction methods are leading to buildings that can withstand hurricane-force winds. However, there are few solutions for the long-term loss of coastal lands caused by erosion. Setback zones, enhanced structures, and beach nourishment can provide temporary solutions, but as sea level continues to rise, line after line of oceanfront development will in the long term be subjected to increasing risks. Some States, including North Carolina, have undertaken systematic statewide shoreline-change surveys in response to coastal-setback legislation. North Carolina maintains high-quality, reliable, shoreline-erosion data that are continually analyzed and updated.

With few exceptions, Outer Banks beaches are eroding 0.6 to 0.9 meter per year (m/yr) (2 to 3 feet per year (ft/yr)). Rapid construction outside public parks and wildlife refuges, coupled with sea-level rise, inevitably led to property damage and loss and then to public demand for coastal management programs directed by State and local governments. Consequently, after several severe storms in the 1960s and 1970s that extensively damaged buildings and infrastructure, North Carolina legislators established the Division of Coastal Management. This State agency focuses exclusively on the management of the State's beaches, barrier islands, inlets, bays, and sounds.

To establish consistent regulatory control of coastal development in high-risk areas, one of the agency's initial steps was to analyze statewide aerial photographs to document historical trends in rates of shoreline change. These data on shoreline erosion rates, updated every 5 years, are used to determine setback positions statewide. (The Division of Coastal Management also provides other useful information about the hazards of coastal living; it is available at http://www.nccoastalmanagement.net).

The North Carolina erosion setback line, landward of which construction may be considered, is measured landward from the first line of vegetation. Setbacks increase with the size of a building; they are determined by multiplying the average annual erosion rate by at least 30. The minimum setback along the Outer Banks is 18.2 m (60 ft) (fig. 42).

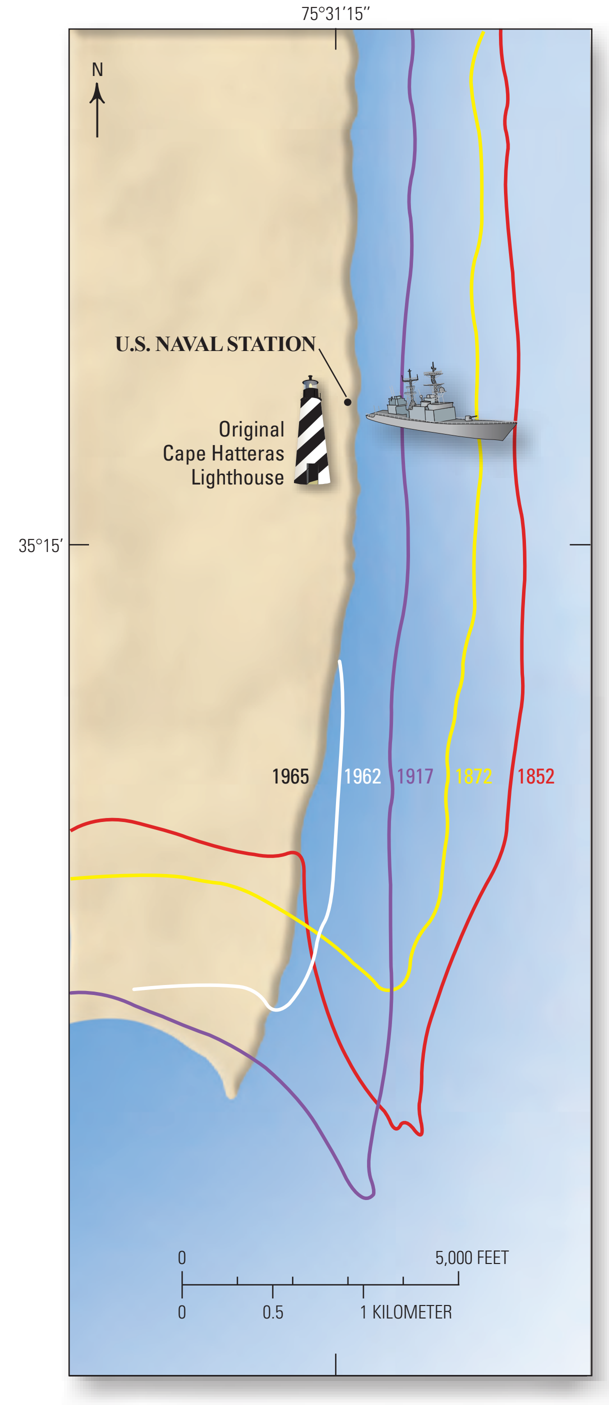


Figure 41. Shorelines change through time. This change is evident when position data from old maps and charts are compared. Construction of the original Cape Hatteras Lighthouse was completed in 1804; note its position relative to the 1852 coastline *(adapted from Fisher, 1967). (Symbols courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).*

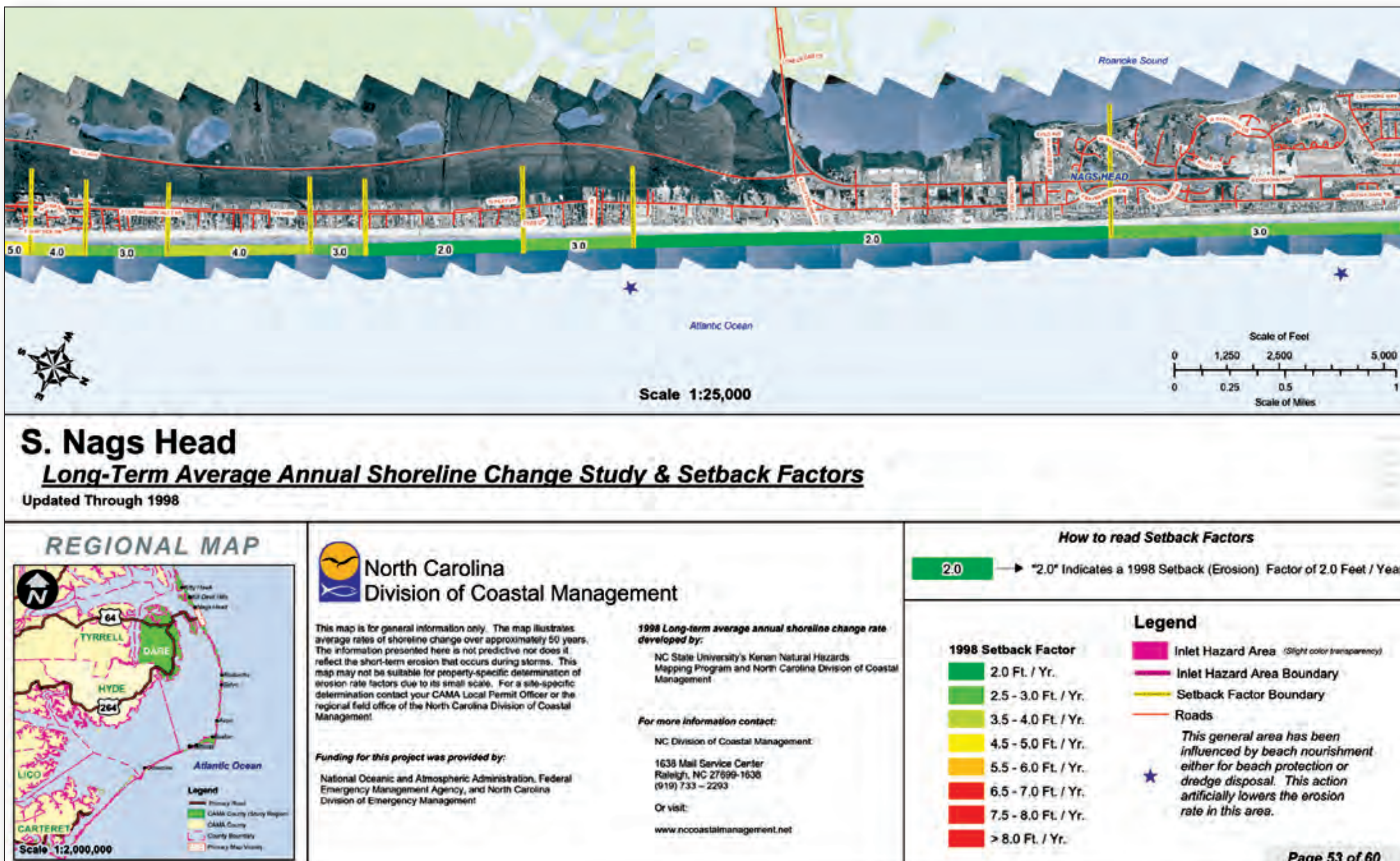


Figure 42. An example of shoreline change maps available from the North Carolina Division of Coastal Management (DCM) (http://www.nccoastalmanagement.net. Accessed January 7, 2013).

Sea rocket
(*Cakile edentula*)

Figure 43. Low-lying sea rocket (*Cakile edentula*), which can grow seaward of the primary dune line, is often the most seaward terrestrial plant. *Photograph by J.J. Smith, March 2002.*

Barrier Island Life

Life is a dance, a very elaborate and complex dance . . .

—C. Singer, 1959, A Short History of Scientific Ideas to 1900

The Outer Banks barrier islands are home to diverse natural ecosystems adapted to the coastal environment. This section introduces the life zones found in a standard cross section of the Outer Banks, and it illustrates some common plants and animals inhabiting the islands. Although humans are also part of the barrier island environment, this section focuses on native flora and fauna.

Coastal barrier islands are harsh places for plants and animals: their sandy soil is nutrient poor; coastal hurricanes and northeast storms cause high winds, flooding, and sediment overwash; plants must tolerate salt spray, wind, and rapidly draining soil; island resources limit terrestrial animals in both size and number. Species robust enough benefit, however. Some plants are specifically adapted to undergo both salt spray and periodic saltwater flooding. Many plants are also succulent, an adaptation to the islands' well-drained sandy soil. At the seaward edge, low-lying sea rocket (*Cakile edentula*) can be found forward of the primary dune (fig. 43) whereas salt marsh cordgrass (*Spartina alterniflora*) rings the lower-energy sound side (fig. 44). The Outer Banks provide an important stopover for birds on the Atlantic flyway, and many species inhabit the islands year round.

Figure 44. Salt marsh cordgrass (*Spartina alterniflora*) fringes the lower-energy sound side of Hatteras Island. *Photograph by J.J. Smith, March 2002.*

Mourning dove
(*Zenaida macroura*)

Northern cardinal
(*Cardinalis cardinalis*)

European starling
(*Sturnus vulgaris*)

Red-winged blackbird
(*Agelaius phoeniceus*)

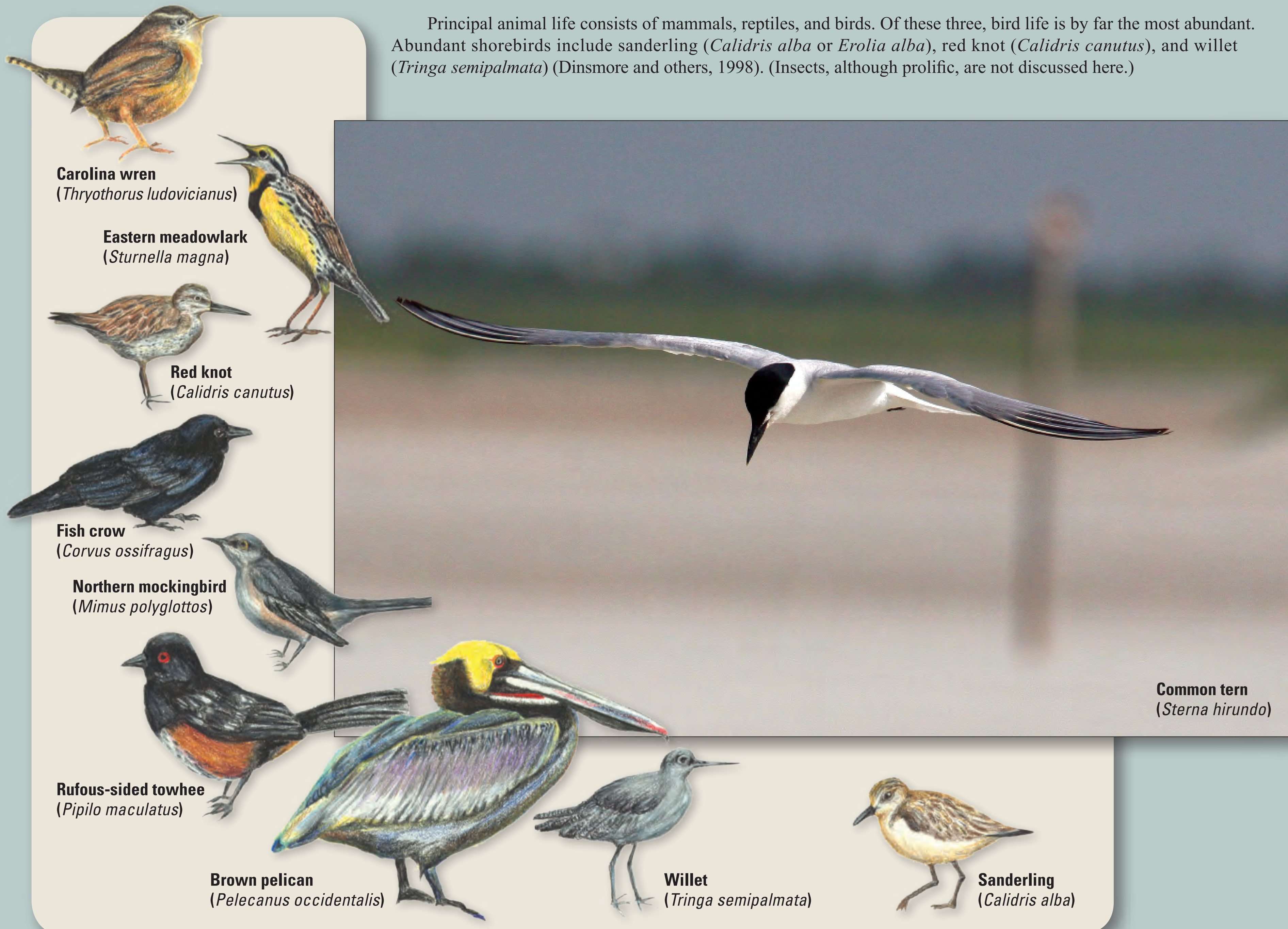
Boat-tailed grackle
(*Quiscalus major*)

Gray catbird
(*Dumetella carolinensis*)

Black skimmer
(*Rynchops niger*)

For the purposes of this report, plant life on the Outer Banks can be considered in three general groups: dune, berm, and grassland vascular plants; woody shrubs and maritime forest plants; and salt marsh plants. The vascular plant community from Ocracoke Island to the Virginia border contains 741 species. Of these, 79 percent are native to the region and about 2 percent are endangered or rare (Stalter and Lamoot, 1997). Only 18 percent of the species are woody. (The islands are also home to freshwater marshes, but they are much less common and are not discussed here.)

Principal animal life consists of mammals, reptiles, and birds. Of these three, bird life is by far the most abundant. Abundant shorebirds include sanderling (*Calidris alba* or *Erolia alba*), red knot (*Calidris canutus*), and willet (*Tringa semipalmata*) (Dinsmore and others, 1998). (Insects, although prolific, are not discussed here.)



Carolina wren (*Thryothorus ludovicianus*)

Eastern meadowlark (*Sturnella magna*)

Red knot (*Calidris canutus*)

Fish crow (*Corvus ossifragus*)

Northern mockingbird (*Mimus polyglottos*)

Common tern (*Sterna hirundo*)

Rufous-sided towhee (*Pipilo maculatus*)

Brown pelican (*Pelecanus occidentalis*)

Willet (*Tringa semipalmata*)

Sanderling (*Calidris alba*)

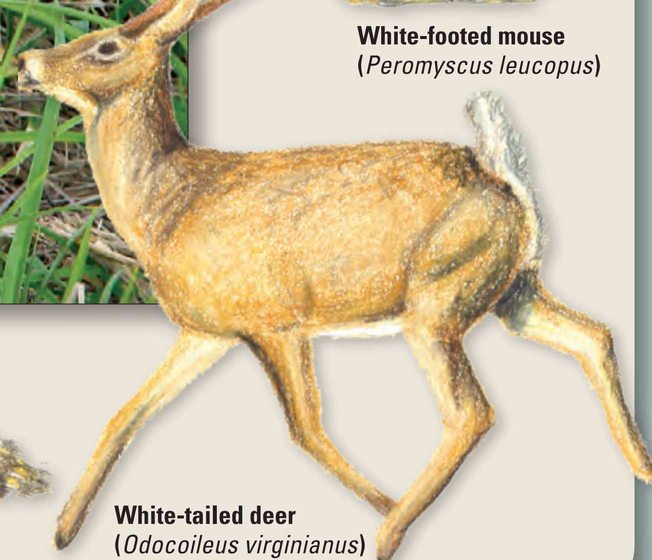
Cottontail rabbit
(*Sylvilagus floridanus*)

Six-lined racerunner
(*Cnemidophorus sexlineata*)

White-footed mouse
(*Peromyscus leucopus*)

Yellow-bellied slider
(*Trachemys scripta*)

Racoon
(*Procyon lotor*)



White-tailed deer
(*Odocoileus virginianus*)

Life Zones on the Outer Banks

Living species, especially plants, commonly inhabit a particular section of the island that has specific physical and ecological characteristics, sometimes called life zones. Life zones on the Outer Banks depend in part on whether the island is undisturbed or whether it has been physically stabilized (fig. 45). A typical undisturbed profile is common in areas such as Core Banks. Life zones of stabilized islands are common in areas such as Hatteras and Bodie. The natural geomorphology of these islands has been altered in several ways, most notably by the construction of a protective seaward dune system designed to halt, or at least slow, movement of the islands and protect the interior from storms.

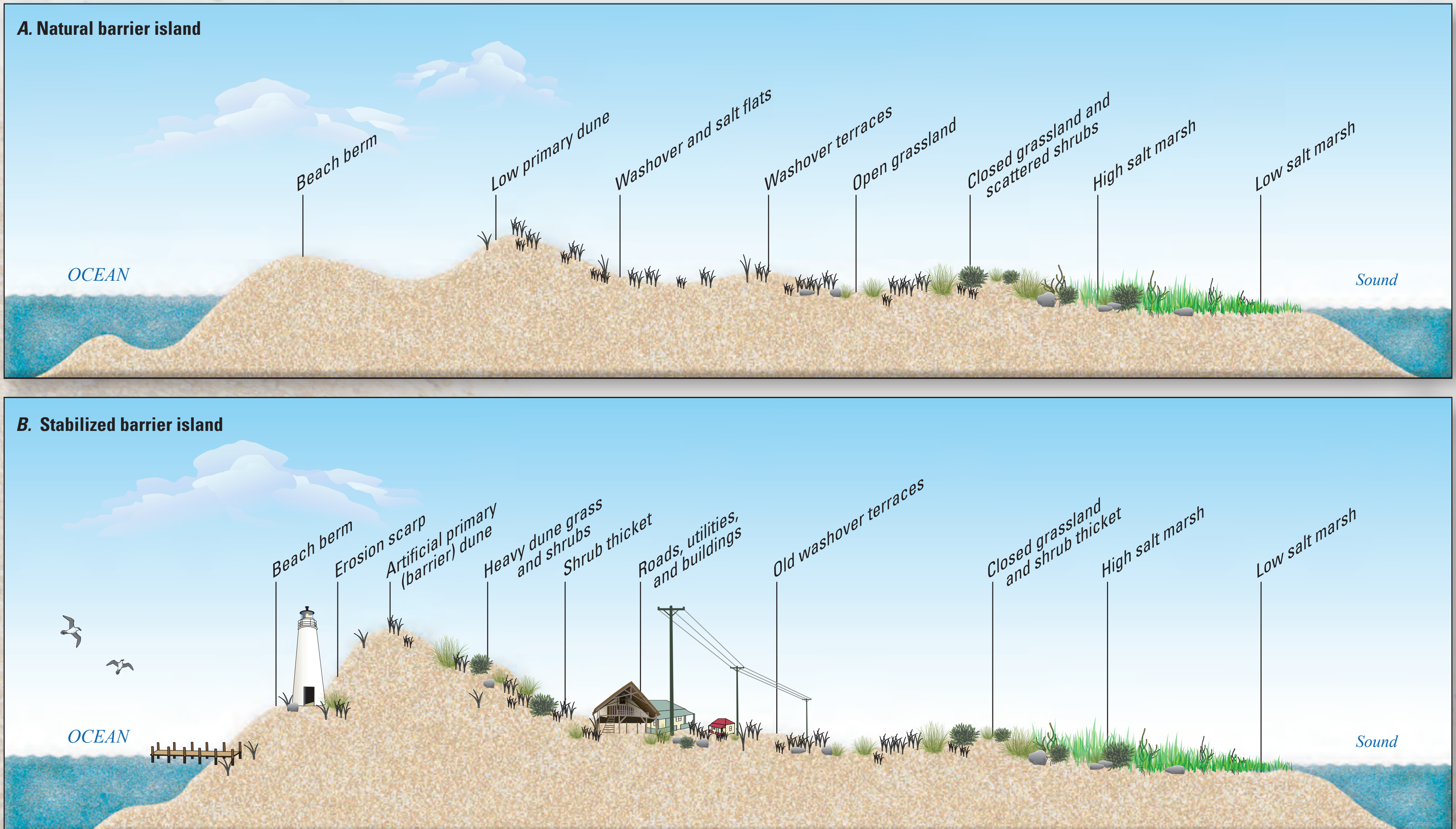


Figure 45. Idealized profiles of a natural (***A***) and a stabilized (***B***) barrier island *(after Dolan, 1973). (Symbols courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).*

Figure 46. Washover fans on Shackleford Banks (looking south), a barrier island in its natural state. Note the wide berm and extensive overwash fans and flats as compared with the stabilized island shown in figure 5. *Photograph by J.J. Smith, June 2002.*

The principal life zones include beach and berm, maritime grasslands, woodlands, fresh marshes, and salt marshes (Godfrey and Godfrey, 1976). The beach on both stabilized and natural islands supports little vegetation and is characterized by a sand apron sloping into the ocean. This area is exposed to tides, storms, and salt water. On a natural island, storm waves and tides carry sand and shells upslope from the beach face to a relatively broad berm that slopes gently toward the interior of the island (Godfrey, 1972a). In contrast, a stabilized barrier beach often has a higher artificial dune marking the beginning of the primary dune system. The primary dunes are typically covered with a variety of grasses.

On a natural barrier island, the berm zone is about 100 to 200 m (325 to 650 ft) wide, depending on the magnitude and frequency of storms. This wide, bare berm serves as a buffer zone that can dissipate wave energy of a moderate storm. Small dunes may form on the berm between storms. Behind the wide berm is a zone of low, irregular dunes broken by washover fans (fig. 46). Storm tides carry sand into the interior of the island through the depressions between dunes. The dunes form as sand accumulates around grasses, such as cordgrass (*Spartina patens*), sea oats (*Uniola paniculata*), and American beach grass (*Ammophilia breviligulata*). The grasses grow upward as the dunes increase in height (Godfrey, 1972b). Behind the dunes at Core Banks, storms have left a series of flat washover terraces (Godfrey, 1970). The highest terraces are overwashed most frequently, and plant distribution depends on the elevation of each terrace above sea level.

Atlantic calico scallop shell
(*Argopecten gibbus*)

Coquina clam shell
(*Donax variabilis*)

Island stabilization has a substantial effect on vegetation, primarily because the stabilized dune line, as high as 10 m (33 ft) in places, commonly prevents overwash and salt spray from reaching the interior of the island. Protected from these natural effects, plants survive closer to the active beach than they normally would. This protection alters the vegetation sequence and allows vegetation to grow more densely on the interior of the island. Inland of the primary dune system on a stabilized island, the dunes transition to a broader and smoother sand flat that may support woody shrubs. Under certain conditions, a maritime forest may exist behind the shrubs and grasslands. Finally, the back of the barrier island is bordered by a gently sloping salt marsh that faces the sound.

In the past, spit formation, beach progradation, and inlet closure left a series of relic dune systems scattered along the Outer Banks. Pine- and oak-dominated woodlands may develop where these dunes are far enough back from the sea to be consistently protected from salt spray (fig. 47) (Oosting and Billings, 1942; Oosting, 1945). Maritime forests on the Outer Banks are found on Shackleford Banks and in scattered form on Core Banks, Ocracoke Village, Buxton, Avon, and Nags Head. These forests probably were never continuous.

Live oak
(*Quercus virginiana*)

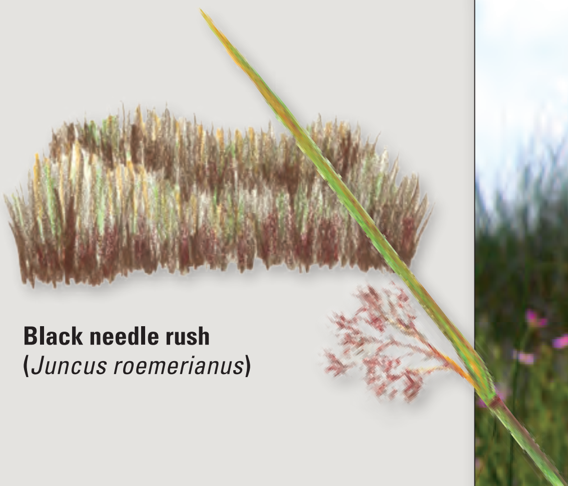
Figure 47. Live oak on Shackleford Banks. *Photograph by Kevin Adams, November 2002.*


Salt meadow cordgrass
(*Spartina patens*)
American beach grass
(*Ammophilia breviligulata*)
Sea oats
(*Uniola paniculata*)

Salt marshes border most of the Outer Banks on the sound side. At the marsh's landward edge, the ground may be flooded only at the highest tide. As it slopes into the sound, the marsh is more and more frequently inundated; the marsh ends at the normal low tide zone.

Salt marshes on the sound side of Core Banks take one of two basic patterns. The first is typically a band of marsh grass, 30 to 50 m (100 to 160 ft) wide, paralleling the dune and grassland zones between the spring high tide mark and normal low tide. Salt marsh cordgrass (*Spartina alterniflora*) dominates the lowest reaches of the marsh. This band of marsh develops on washover terraces within reach of the tides. Currently, washover deposits that fill part of the sound support the richest stands of marsh grasses.

The second salt marsh pattern is found on numerous small islets directly behind the main barrier island. There, grasses develop on old tidal deltas left by former inlets (Fisher, 1962). Occasionally, overwash sediment fills in the sound and joins the marsh islets to the main barrier island. The islets have the same life zones as the fringing marshes, except that black needle rush (*Juncus roemerianus*) may replace the cordgrasses in areas not regularly flooded by tides.



Black needle rush
(*Juncus roemerianus*)

Native Vegetation

Some uncertainty exists about the extent of vegetation on the islands before the arrival of the first English settlers. The earliest reliable accounts that describe conditions when European explorers arrived date from the late 18th century. By then, Europeans had inhabited the islands for at least 100 years and had introduced large numbers of cattle, sheep, horses, and hogs (Dunbar, 1958). Although extensive vegetation may have covered the islands originally, grazing and woodcutting by early settlers partially stripped the islands of their grasses and trees and created an unnatural, desolate condition (Cobb, 1903). At Portsmouth, on the northern tip of Core Banks, a single resident reported that he "Sheared 700 head of Sheep—had between two hundred fifty and three thousand head of cattle and near as many horses" (Dunbar, 1958). The Outer Banks may recover from overgrazing more quickly than once thought, however. Following the removal of grazing animals from Portsmouth, vegetation reestablished itself without human intervention, and a system of dunes with an orderly succession of vegetation developed rapidly (Burk and others, 1981).

On the other hand, although humans and domestic animals undoubtedly depleted Outer Banks vegetation, several investigators have observed that vegetation on the islands was naturally rather sparse (fig. 48). Regular episodes of overwash and flood tides preclude the establishment of permanent forests, except at a few high dune areas such as Buxton and Nags Head Woods.

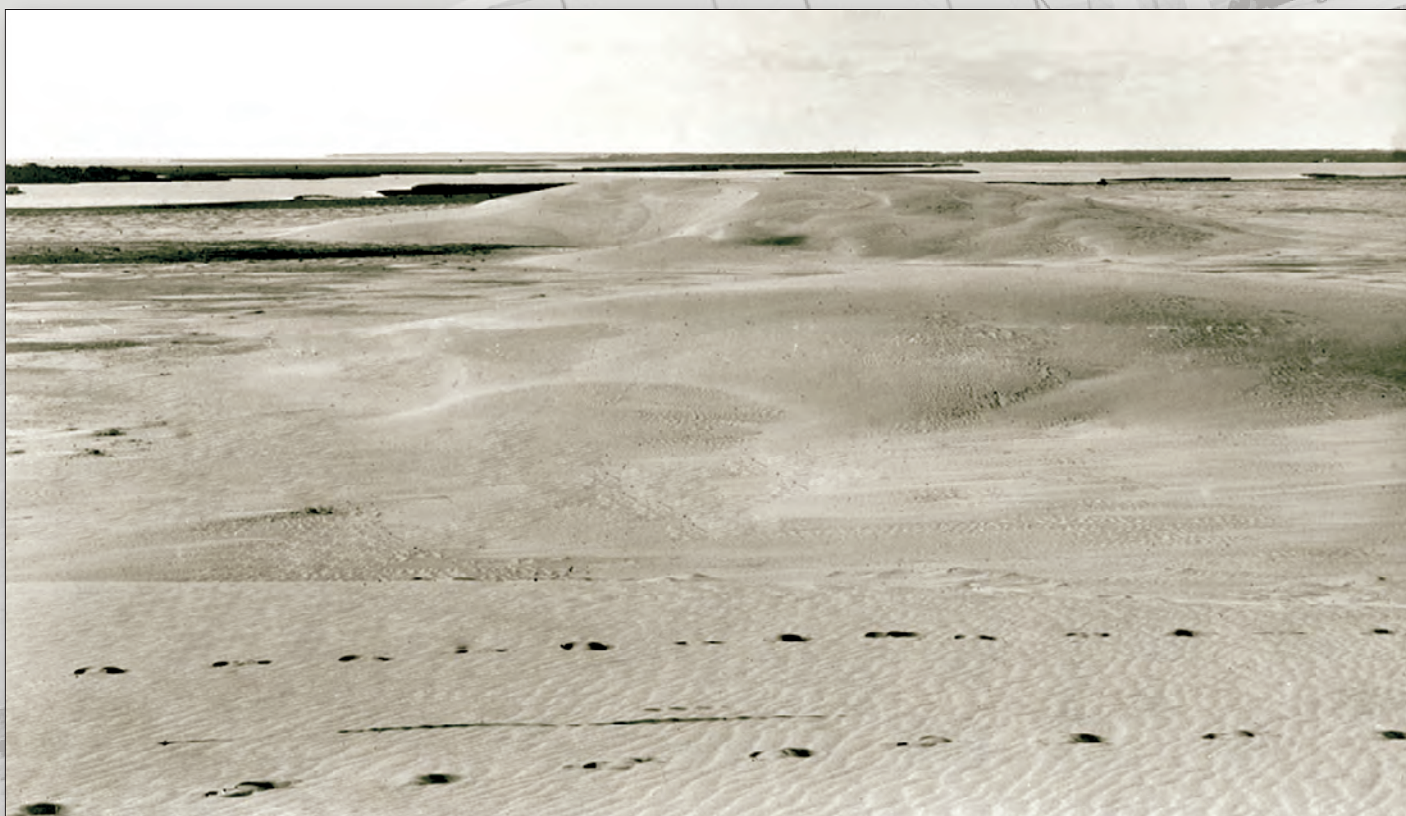


Figure 48. View from the top of Kill Devil Hill, Kitty Hawk, North Carolina, 1901. *Courtesy of the Library of Congress, Prints and Photographs Division, LC-DIG-ppprs-00578; photograph by Wilbur or Orville Wright.*

Figure 49. Seabeach amaranth (*Amaranthus pumilus*), a federally listed threatened plant, is found on Cape Lookout National Seashore. *Photograph by Bill Adams, courtesy of U.S. Fish and Wildlife Service.*

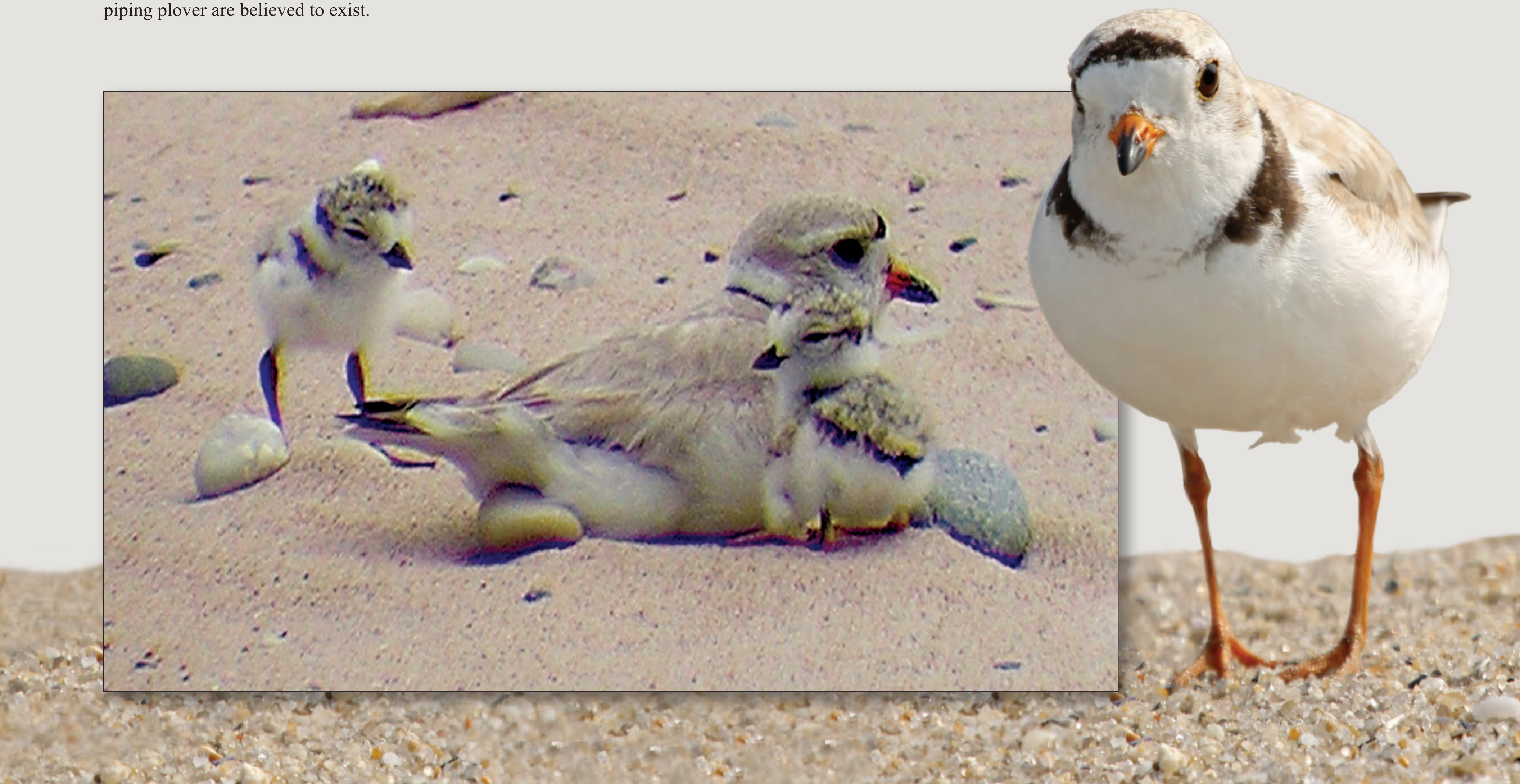
Figure 50 (facing page). Piping plover with chicks. *Photograph by Alice van Zoeren, courtesy of the National Park Service.*

Endangered and Threatened Species

The federally listed threatened plant seabeach amaranth (*Amaranthus pumilus) (*fig. 49) colonizes parts of Cape Lookout National Seashore, primarily on sand flats, and on lower foredunes and upper strands of stable beaches. Amaranth is the only known endangered or threatened plant on the Outer Banks.

Outer Banks beaches provide an important nesting habitat for five endangered or threatened sea turtle species: leatherback (*Dermochelys coriacea),* green (*Chelonia mydas*), loggerhead (*Caretta caretta*), hawksbill (*Eretmochelys imbricata*), and Kemp's ridley (*Lepidochelys kempii*). On Cape Hatteras National Seashore during the 2007 nesting season (April through August), these species constructed 82 nest sites and 6,075 hatchlings emerged.

The endangered roseate tern (*Sterna dougallii*) is an occasional visitor to the islands, especially near Cape Hatteras. The threatened piping plover (*Charadrius melodus*) (fig. 50) nests along the beach dunes in late March or early April. Recreational and commercial development, along with dune stabilization, has reduced its nesting habitat, and fewer than 2,000 nesting pairs of piping plover are believed to exist.



Part II: Human History and Modern Development of the Outer Banks

History

Aboriginal People

And see the children sport upon the shore,

And hear the mighty waters rolling evermore.

—William Wordsworth, 1807, Ode: Intimations of Immortality from Recollections of Early Childhood

Humans began inhabiting the North Carolina area at least 12,000 years ago, but little is known about those who may have eventually made their homes on the Outer Banks. No formal record exists of those early people. Wave action and wind commonly disturb or destroy archeological evidence used to discern the lives of early people, and few clues are left behind. Landward movement of the islands destroys or submerges potential archeological information. In addition, the lack of evidence may relate directly to lack of archeological research in this area (David Phelps, East Carolina University, oral commun., 2007)—the Coastal Plain is probably the least understood of the archeological physiographic regions in North Carolina.

With the establishment of Cape Hatteras National Seashore, the National Park Service began to investigate the origins of human settlement in this area. Although the date of the first human settlement on the Outer Banks has not been determined, the natives who met the first European settlers in the late 1580s "had lived in the same general territory since AD 800" (Price and others, 2008).

Two permanent tribes are thought to have inhabited the Outer Banks at the time of English settlement: the Roanoac tribe on Roanoke Island, and the Croatoan on Hatteras Island near present-day Buxton. Colington Island appears to have been a summer home to native tribes. Outer Banks natives were geographically isolated and thought to have been less developed culturally (Haag, 1956) than the Algonkians who occupied other areas of the eastern United States.

Written accounts by English explorers offer some insight into the native population. Native peoples were of medium stature, lived in small villages of perhaps 8 to 30 homes, and were ruled by a chief whose role may have been passed on through the mother's lineage (fig. 51). The chief and nobles were the political and religious center of the groups. Agriculture, hunting, and fishing were sources of subsistence, and shellfish was the staple food (Haag, 1956).

By AD 1650, the coastal population of native Algonkian had markedly declined, probably as a result of disease and the establishment of European colonies (Price and others, 2008). As noted by Haag (1956), the native "Coastal Carolinians disappeared quite as suddenly and dramatically as the Lost Colony."

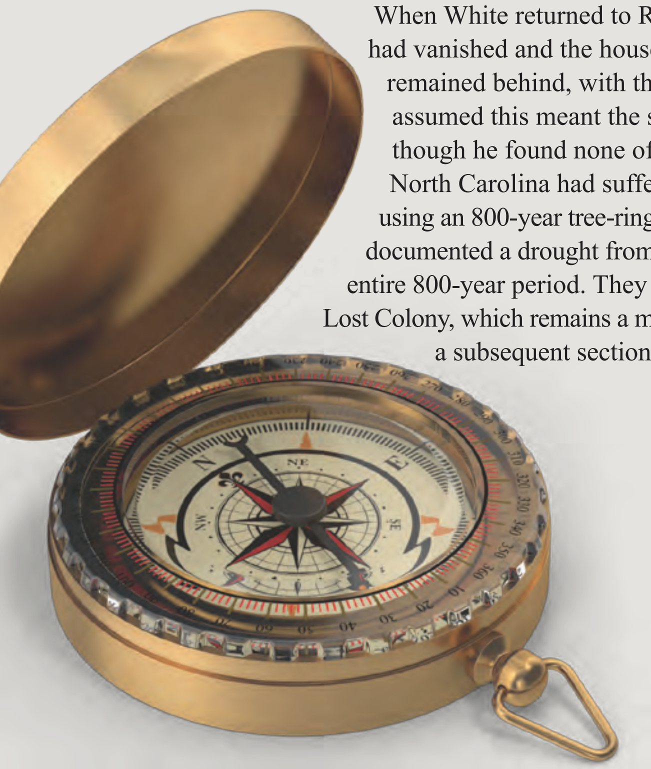
Figure 51. John White included this portrayal of "A cheiff Lorde of Roanoac" in his illustrations of the Walter Raleigh explorations *(from Hariot, 1588). Engraving by Theodor de Bry. Electronic image courtesy of EagleRidge Technologies at http://www.roanetnhistory.org/hariot-debry-virginia.php?loc=Hariot-DeBry-Briefe-True-Report-Virginia&lang=us&pgid=44*

European Settlement

European explorers discovered the North Carolina barrier islands in the 16th century but did not permanently settle them until the middle 17th century. English explorers first attempted to colonize North America on the northern end of Roanoke Island. The most well-known venture was the "Lost Colony" in 1587, but other settlers made several related and failed attempts to establish a community in this location. Walter Raleigh spearheaded efforts to colonize the North Carolina area after his own 16th century exploration near the Outer Banks. He organized and partially financed Sir Richard Grenville's 1585 expedition that established the first known English community on the northern end of Roanoke Island. In July of the following year Grenville returned to the colony with additional supplies from England but found no one remaining in the settlement. As it turned out, a fleet under the command of Sir Francis Drake had visited the settlement unexpectedly in June of 1586 and the settlers, whose supplies had run critically low and who did not know the status of the resupply voyage, had returned to England on Drake's ships.

In 1587, Raleigh made the first serious attempt at long-term colonization. A group of men, women, and children led by John White arrived on Roanoke Island and, once again, no one from Grenville's party was recovered. White's company renamed the settlement the "Cittie of Ralegh." In the summer of 1587, White's granddaughter, Virginia Dare, became the first child born in the colonial United States to English parents. John White returned to England on August 27, 1587. He arrived to find England on the verge of war with Spain, and thus he had difficulty finding suitable ships for the colony's relief.

When White returned to Roanoke Island in the summer of 1590, the settlers had vanished and the houses had been dismantled. A crude fort-like settlement remained behind, with the word "Croatoan" carved into a tree or post. White assumed this meant the settlers had joined the friendly Croatoan Indian tribe, though he found none of them. During White's absence, the tidewater area of North Carolina had suffered an intense drought (Stahle and others, 1998). By using an 800-year tree-ring chronology from bald cypress, Stahle and others (1998) documented a drought from 1587 to 1589 that was the most extreme drought of the entire 800-year period. They speculated that it was likely a factor in the fate of the Lost Colony, which remains a mystery. (For more information about the Lost Colony, see a subsequent section, Shoreline Erosion and the Lost Colony.)



The first permanent settlement on the Outer Banks was founded in 1663 on present-day Colington Island (fig. 52), where English colonists settled within dune fields on the sound side of the island. The dunes provided timber, fuel, freshwater, and protection from strong winds and storm tides. Selling oil extracted from whales that washed up on shore was the most profitable occupation, but the availability of extensive unfenced grazing land soon led to a livestock industry (Stick, 1958).

Before 1700, most settlements were located between Roanoke and Currituck Inlets. As Roanoke Inlet began to shoal and eventually close, however, maritime traffic diverted 120 km (75 mi) south to Ocracoke Inlet. By 1750, hundreds of ships used Ocracoke Inlet as a trade route. The town of Portsmouth, south of Ocracoke Inlet, grew rapidly as a transshipment point for goods bound for the Carolina colony's interior (fig. 52).

Figure 52. The Outer Banks of North Carolina during the colonial period *(after Stick, 1958).*

Eastern red cedar
(*Juniperus virginiana*)

Loblolly pine
(*Pinus taeda*)

Industrial Beginnings

A few wealthy businessmen controlled most land on the Outer Banks in the 1700s. However, by the end of the Revolutionary War, many of the largest holdings had been subdivided into small plots, and new construction began. Shipbuilding and lumber industries were among the most successful trades in the early 1800s (Stick, 1958), and live oak, pine, and cedar forests were rapidly depleted. Livestock grazed on the open dunes. American independence created a new sense of nationalism, increased the desire of local settlers ("Bankers") to acquire land titles, and gave impetus to improving transportation routes and constructing lighthouses to make ocean travel safer.

Surprisingly, commercial fishing was not a primary source of income for most early residents of the Outer Banks, even though data from 1850 indicate that many locals considered themselves boatmen and mariners, pilots, or seamen (Stick, 1958). Between the Civil War and World War II the commercial fishing industry expanded, though the difficulty in delivering fresh seafood to commercial markets limited its development. Area fishing industries concentrated on species they could preserve with salt or smoke, or from which oil could be extracted. Another hallmark of Outer Banks fishing was that it was generally conducted from the shore, or from boats weighing less than 5 net tons (Stick, 1958).

Shipping lanes off the North Carolina coast are among the most treacherous on Earth. The northward-flowing Gulf Stream in combination with the southward-flowing littoral drift, which is closer to the shoreline of the northern Outer Banks, increased the speed of sailing vessels traveling north and south along the Outer Banks, but they also obliged ships to navigate dangerously close to shore (Roush, 1968). Before the construction of lighthouses, hundreds of vessels were lost during storms when they were driven onto the shoals or the coast. The area around Cape Hatteras known as Diamond Shoals came to be known as the "Graveyard of the Atlantic." (Shipwrecks on the Outer Banks are discussed at greater length in a subsequent section, Shipwrecks.)

Lighthouses and Lifesaving Stations

Responding to the demand for navigational aid and to prevent shipwrecks and loss of life, the Federal government built lighthouses and lifesaving stations on the Outer Banks. By 1883, five coastal lighthouses and 25 "life saving" stations lined the Outer Banks coastline (Stick, 1958). The five coastal lighthouses are, from north to south, Currituck Beach, Bodie Island (fig. 53), Cape Hatteras (fig. 54), Ocracoke, and Cape Lookout (fig. 55). Mariners can visually identify all five by their unique color or pattern. The first was built at Ocracoke inlet on Shell Castle island beginning in 1794. However, Ocracoke inlet migrated more than a mile in the succeeding 30 years, rendering the lighthouse obsolete even before lightning destroyed it in 1818. The U.S. Lighthouse Establishment completed the standing Ocracoke Lighthouse in 1823. Construction of the Currituck Beach Lighthouse concluded in 1875. During the years between 1794 and 1875, the three other coastal lighthouses were erected. All five were automated between 1936 and 1955 and are still operational.

Bodie Island Lighthouse

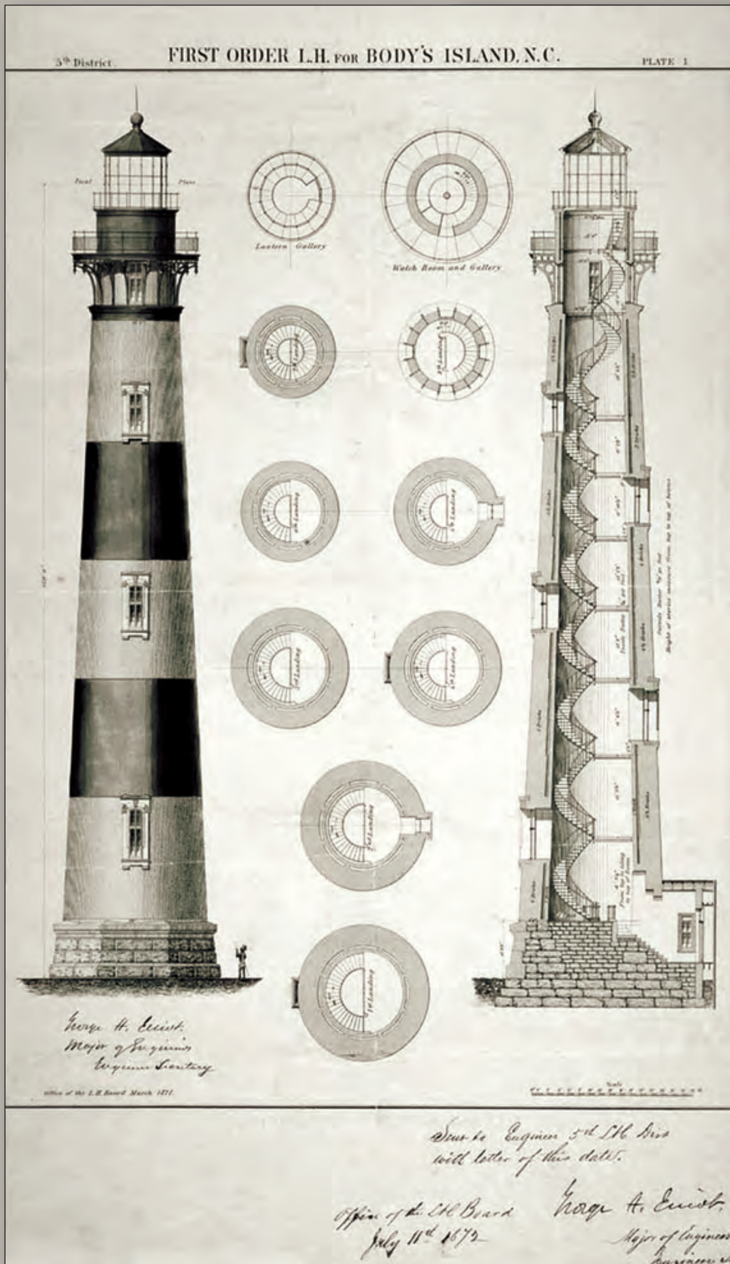


Figure 53 (left). Architectural drawing of the Bodie Island Lighthouse, 1871. *Courtesy of the U.S. National Archives and Records Administration, Mid-Atlantic Region, Philadelphia.*

Cape Hatteras Lighthouse

Figure 54. Cape Hatteras Lighthouse in its original location. *Photograph by Clifton Adams, courtesy of the National Geographic Society, 1933.*

Cape Lookout Lighthouse

Figure 55. Cape Lookout Lighthouse. *Photograph by J.J. Smith, June 2002.*

In addition to the better-known lighthouses on the islands, the Federal government also deployed ships fitted with lights as navigational aids (lightships) and fabricated smaller lighthouses mounted on piles screwed into the shallow bottom (screw-pile lighthouses) in the sounds. Lightship stations in Pamlico Sound included the Harbor Island, Long Shoal, Nine Foot Shoal, Royal Shoal, and Brant Island Shoal. A permanent tower replaced the Diamond Shoals Lightship in 1966 (fig. 56), marking Diamond Shoals in the Atlantic Ocean. This tower was heavily damaged by Hurricane Fran in 1996 and was deactivated in 2001. The light was subsequently removed, although the tower still stands.

Screw-pile lighthouses, more modest in appearance than their tall cousins, identified hazardous estuarine sites. Roanoke Marshes and Croatan Shoal (fig. 57) Lighthouses marked channels in Croatan Sound. Their final towers were lit in 1877 and 1887 respectively. A replica of the Roanoke Marshes Lighthouse now stands in the town of Manteo (fig. 57 *background photograph).*

Figure 56 (left). Diamond Shoals Lightship, which was intermittently stationed about 24 kilometers (15 miles) from the Cape Hatteras Lighthouse between 1824 and 1966. A permanent tower replaced it in 1966. *Photograph courtesy of the U.S. Coast Guard.*

Figure 57 (facing page). Roanoke Marshes screw-pile lighthouse. ***Inset photograph***, Original lighthouse built in 1877 on Croatan Sound; ***Background photograph***, Current reproduction at the Roanoke Island Maritime Museum. ***Inset photograph****, courtesy of the U.S. National Archives and Records Administration, 26-LG-22-76;* ***Background photograph****, courtesy of the Town of Manteo.*

Lifesaving stations (fig. 58) first appeared on the Outer Banks in 1874 when the U.S. Life-Saving Service expanded its duties to include North Carolina. The first seven stations were built by December of that year (Stick, 1958) and were manned by a keeper and six surfmen whose job was to aid imperiled persons on the water. The first operational station, in present day Rodanthe, was Chicamacomico (an Algonquian word meaning "land of shifting sand").

To rescue mariners, the U.S. Life-Saving Service used either a surfboat (fig. 59) or a line reaching from the beach to the stranded vessel. Both methods required courage and skill, and many surfmen lost their lives during rescues. Crews were experts on weather and surf conditions because of their long residence and service in a single area.

The U.S. Life-Saving Service existed from 1848 until 1915, when the Federal government merged it and the U.S. Revenue Cutter Service, creating the U.S. Coast Guard. Today, the Coast Guard, as part of the Department of Homeland Security, protects those imperiled on Outer Banks waters. Three boat stations, two full-time and one seasonal, are located at Oregon Inlet, Hatteras Inlet, and Ocracoke Island.

Figure 58 (left). U.S. Life Saving Station in Kill Devil Hills, 1902. *Photograph courtesy of the Library of Congress.*

Figure 59 (facing page). Original Beebe-McLellan surfboat located at the Chicamacomico Life-Saving Station Historic Site, Rodanthe, North Carolina ***(inset photograph)***. Crew members used this double-ended, self-bailing, self-righting boat with six oar positions in the rescue of 42 British merchant seamen from the vessel *Mirlo* in 1918 *(Photograph by J.J. Smith)*; Oregon Inlet Life-Saving Station ***(backgound photograph)***. *Photograph courtesy of William Birkemeier.*

Island Engineering and the Beginning of Tourism

When Roanoke Inlet closed in 1811, people became concerned that Ocracoke Inlet might also close. As a result, Federal government engineers first attempted to alter natural processes along the Outer Banks in the 1830s by using a special dredging machine to deepen and widen the shipping channel. The dredge was about 20 m (65 ft) long and was propelled by steam-driven paddle wheels (fig. 60). Buckets mounted to a conveyor belt that ran through a shaft in the vessel's hull scooped sand from the channel bottom onto scows that then dumped the sand onto nearby shoals. Work continued until 1835, when engineers concluded that Ocracoke's main channel filled as fast as they could dredge it (Stick, 1958).

In 1828, Currituck Inlet closed and Ocracoke became the only navigable inlet north of Cape Lookout. In 1846, a storm breached the Outer Banks in two places, forming Oregon and Hatteras Inlets. Within 20 years, shipping through Ocracoke Inlet and thus industry in the town of Portsmouth decreased substantially, and Hatteras Inlet surpassed Ocracoke as the most-traveled inlet on the North Carolina coast.

Vacationers were first reported on these barrier islands as early as 1750 (Stick, 1958). In 1838 the first hotel was constructed at Nags Head with accommodations for 200 guests. Like the first colonists, summer residents were aware of potential erosion and storm tide hazards, and the hotel and many cottages were built on the sound side. Nags Head became known as a favorite "watering place" where wealthy mainland North Carolinians could escape the heat and fevers of malaria rampant at that time (Stick, 1958).

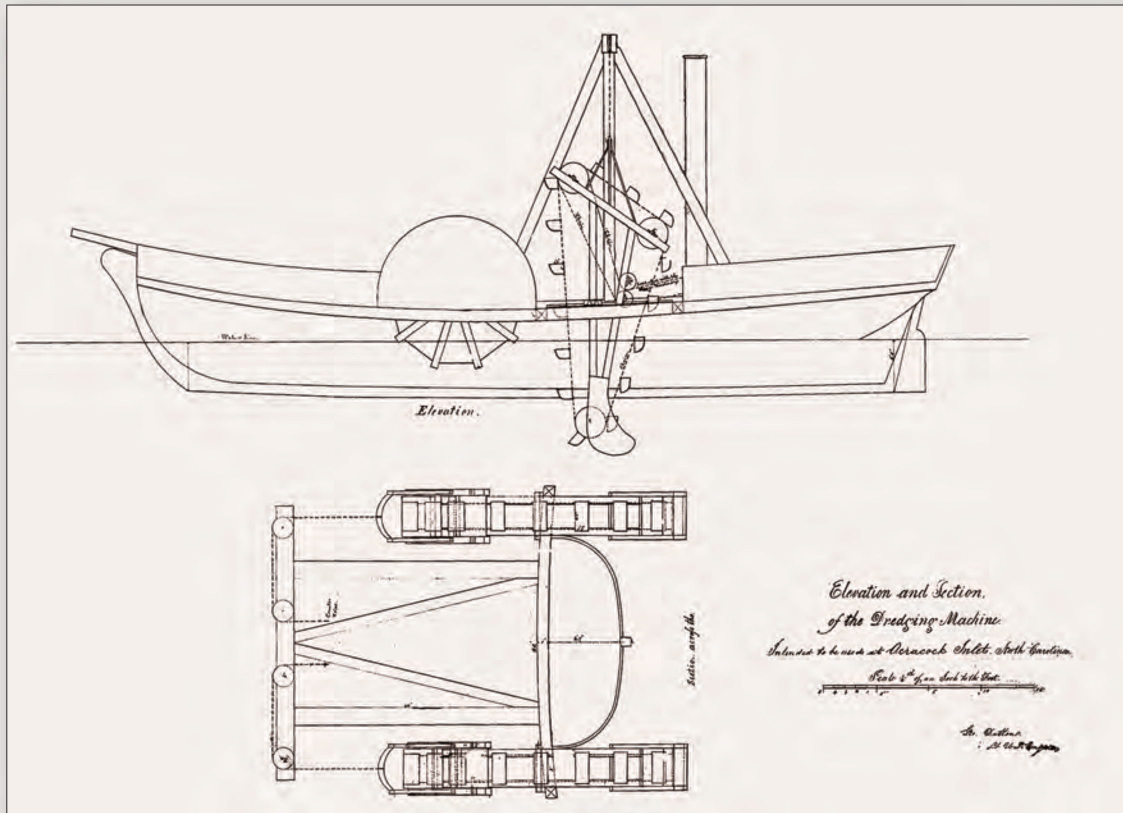


Figure 60. Image of the original drawing of the first dredge used to maintain inlets on the Outer Banks. *Photograph courtesy of the U.S. National Archives and Records Administration.*

After the Civil War

After the Civil War, the Outer Banks changed in three important ways. First, shipping traffic continued to withdraw from Ocracoke Inlet (following the opening of Oregon and Hatteras Inlets in 1846). Portsmouth declined from its 1860 population of 685 to 17 in 1956. In 1971 the last permanent residents departed Portsmouth, and in 1976 it became part of Cape Lookout National Seashore. Second, to accommodate summer residents returning after the war, a new hotel was built at Nags Head (fig. 61). The original Nags Head Hotel had been burned to keep Union forces from using it as a base of operations. Third, some summer residents began building cottages on the ocean side of the island. This departure from the traditional practice of building on the more protected sound side placed more houses at risk of direct impact by storm waves.

Figure 61. Nags Head Hotel in 1898. *Photograph courtesy of the National Park Service.*

Aviation History

Important aviation advances took place on the islands, such as the Wright Brothers' first powered flight (1903) and General Billy Mitchell's bombing exercises in the early 1920s that led to the development of the U.S. Air Force. The better-known and more historically important achievement was Wilbur and Orville Wright's first flight at Kitty Hawk. Their 12-second flight marked the first time a manned, heavier-than-air machine left the ground by its own power, moved forward under control without losing speed, and landed on a point as high as that from which it started. The site of their experiments is now incorporated into the Wright Brothers National Memorial at Kitty Hawk. The first flight took place on the Outer Banks specifically because of its geography and climate. The brothers sought "an isolated location that had a steady wind with rolling hills and long flat beaches for launching, flying and landing" gliders (Price, 2008) (fig. 62).

Army General Billy Mitchell used the waters near the Outer Banks in 1923 for an early demonstration of strategic air power. Martin bombers effectively targeted and sank two derelict battleships about 32 km (20 mi) from Cape Hatteras. Mitchell himself took off from a temporary airfield near Hatteras Village that locals had quickly constructed to support his mission. Today, the North Carolina Department of Transportation, in conjunction with the National Park Service, operates the Billy Mitchell Airport at that location (fig. 63). Personal controversies, including General Mitchell's court-martial for insubordination, may have delayed the adoption of his theories on air power by the United States military during his lifetime. However, the Second World War soon vindicated his ideas. He was posthumously awarded the Congressional Gold Medal in 1946.

Figure 62 (below). The Wright glider making an in-flight turn at Kitty Hawk, North Carolina, 1902. *Photograph from U.S. Army Air Service, Aerial Photograph Section No. 3, Bolling Field, Washington, D.C., courtesy of Maxwell Air Force Base.*

Figure 63 (inset photograph). Billy Mitchell Airfield at Hatteras, North Carolina. *Photograph by J.J. Smith, August 2008.*

Development of Modern Tourism

At the time of the Great Depression, little industry existed on the Outer Banks. The cattle strain had not been improved and shipping traffic consisted mainly of small private boats, but improved navigation aids did decrease the number of shipwrecks (Stick 1958). Construction of bridges and paved roads in the 1920s and 1930s markedly increased the number of summer visitors. A paved road had been constructed near the shoreline and, unlike previous tourists, seasonal occupants now preferred staying on the ocean side of the islands. Because land values were low and household utilities minimal, residents had little concern with dangers of building close to the beach. During periods of severe erosion, homeowners could move their cottages back to safer positions. The Carolina Development Company began marketing and building properties at Virginia Dare Shores in what is now Kill Devil Hills (fig. 64). These properties, the Outer Banks' first coastal housing development, were just an overnight trip by steamer from Washington, D.C., and Baltimore.

In 1933, after one of the most severe hurricanes on record, the National Park Service and the Civilian Conservation Corps proposed a massive sand-fixation program to stabilize the moving sand (Croft, 1934), because storm waters could sweep across some parts of the island from ocean to sound. Between 1933 and 1940, workers in this program constructed more than 900 km (600 mi) of sand fencing on 185 km (115 mi) of beach. To stabilize the dunes further, they also planted 13 million square meters (140 million square feet) of grass and 2.5 million seedlings, trees, and shrubs (Dunbar, 1958). In 1935, free-ranging livestock was prohibited from Currituck to Hatteras Inlet, and in 1937 the National Park Service proposed establishment of the Cape Hatteras National Seashore (Roush, 1968). (The dune stabilization program is described in a subsequent section, Engineering Projects on the Outer Banks.)

Figure 64. This house, at the corner of East Walker Street and Virginia Dare Trail in Kill Devil Hills, North Carolina, is one of the few remaining original homes from the Virginia Dare Shores subdivision. *Photograph by J.J. Smith, August 2008.*

National Seashores

Authorized by Congress in 1937 and completed in 1953, the Cape Hatteras National Seashore (30,000 acres) encompasses most of the Outer Banks between Nags Head and Ocracoke Inlet (fig. 65). The national seashore excludes some areas, among them Pea Island National Wildlife Refuge and several local villages. National Park Service ownership prevented construction south of Nags Head except in exempted villages. Headquartered at Manteo, the Park Service also holds jurisdiction of the Wright Brothers National Memorial at Kill Devil Hills and the Fort Raleigh National Historical Site on Roanoke Island.

Two primary factors prompted establishment of the first national seashore. First, these lands were among the world's best examples of barrier island environments, of high quality and rich diversity. Second, erosion was becoming a serious problem amid growing concern that the islands would soon disappear. Although the shoreline retreated to within about 45 m (150 ft) of the Cape Hatteras Lighthouse and coastal development was rapidly continuing, a proposal to place the property under Federal control generated considerable disagreement. In 1952, Paul Mellon and his sister Ailsa donated $800,000 to purchase the land. This purchase, combined with the State of North Carolina's matching gift and the efforts of key individuals, was instrumental in the national seashore's creation (Stick, 1958).

Cape Hatteras National Seashore is distinct from a national park because it was established with the intent to both preserve the barrier islands and facilitate their recreational use (Binkley, 2007). In addition, during the Great Depression, President Franklin Roosevelt's administration was able to concentrate work-relief programs such as the Works Progress Administration and the Civilian Conservation Corps on Federal property.

Congress authorized Cape Lookout National Seashore in 1966 before Core and Shackleford Banks underwent major development. Even though the national seashore was not officially transferred to the National Park Service until 1976, this authorization prevented many problems that occurred north of Cape Hatteras. The boundaries of the park extend 93 km (58 mi) from Ocracoke Inlet to Beaufort Inlet and contain Portsmouth Island, Core Banks, and Shackleford Banks (24,500 acres). Cape Lookout National Seashore has no roads or bridges and remains, for the most part, in its natural state.

Figure 65. National seashores and national wildlife refuge on North Carolina's Outer Banks.

Shipwrecks

Shipwrecks figure prominently in the history and culture of the Outer Banks, and its shifting underwater landscape has earned the nickname “Graveyard of the Atlantic” because so many vessels sank in these waters (fig. 66). Before modern communication, surveying and navigation, shipwrecks were more common and difficult to inventory. The low, flat Outer Banks are difficult to see and are remote. Lacking the maneuverability of modern ships, sailing vessels were more susceptible to running aground on submerged shoals or succumbing to convoluted wind and weather. The National Park Service provides locations and descriptions of some wrecks that may be visible to visitors—the *Laura Barnes, Lois Joyce, Oriental,* and *G.A. Kohler.*

The warm Gulf Stream and cold Labrador currents merge at Cape Hatteras at the treacherous Diamond Shoals. In addition, mariners navigate the Cape Lookout shoals, which extend a shallow finger hundreds of meters offshore. By the middle of the 20th century, more than 600 vessels had been lost off the coast of North Carolina from the Virginia border to Cape Fear (south of map area, near Wilmington, NC) (Stick, 1952). Between 2002 and 2005, the National Oceanographic and Atmospheric Administration’s Ocean Exploration Program and East Carolina University conducted the Ocracoke Shipwreck Survey to identify and document these lost cultural resources. The survey combined historical research with remote sensing to inventory and position wreck sites. As a result, more than 2,000 wrecks were documented between Capes Hatteras and Lookout (Runyan, 2006).

Some wreck survivors helped to populate the Outer Banks by remaining on the islands to raise families. Lost cargo provided an income for island inhabitants and salvaged timber from wrecks supplied building material. In addition, the isolated sounds behind the islands provided refuge for pirates such as Blackbeard, Stede Bonnet, Anne Bonny, and Calico Jack Rackam (Stick, 1952).

Figure 66. The vessel *Antonin Dvorak* the day after it drifted ashore in March 1959. *Photograph courtesy of the National Park Service, Superintendent’s Monthly Narrative Report for Cape Hatteras National Seashore, March 1959, Cape Hatteras (CAHA) archives.*

Documenting Shipwrecks.—Determining the number of ships wrecked on the Outer Banks is difficult, especially for wrecks before modern times. Previously, shipwreck documentation relied heavily on witnesses, word of mouth, and historical documents. However, modern equipment indicates that the number of wrecks is far greater than previously imagined. David Stick's book *Graveyard of the Atlantic* (1952) was one of the first definitive historical works on the subject of Outer Banks shipwrecks. The more recent Ocracoke Shipwreck Survey documented wrecks in a zone extending for 3 mi on each side of the Outer Banks islands between Cape Lookout and Cape Hatteras. An additional zone with a 16-km (10-mi) radius around the Ocracoke Lighthouse was also inventoried (Runyan, 2006). Traditional historical research, as well as field magnetometer, side-scan sonar, and global positioning system equipment were used in the Ocracoke survey to document the more than 2,000 wrecks.

Historically Important Shipwrecks.—Several ships that wrecked off the Outer Banks are historically important, such as the USS *Monitor*, one of the first ironclad steam warships (fig. 67). The *Monitor* is also known for its meeting at the Battle of Hampton Roads (Virginia) with the ironclad Confederate ship the CSS *Virginia* (formerly the USS *Merrimac*) on March 9, 1862. Although neither ship won a decisive victory, the confrontation ended the preeminant position of wooden-hulled sailing warships (U.S. National Oceanic and Atmospheric Administration, 2007).

The *Monitor* sank during a storm on New Year's Eve 1862, about 26 km (16 mi) southwest of Cape Hatteras in 72 m (235 ft) of water. Four officers and 16 crewmembers died. A crew working on a Duke University research vessel discovered the *Monitor* in 1973 (fig. 68). The site became the United States' first National Marine Sanctuary in 1975.

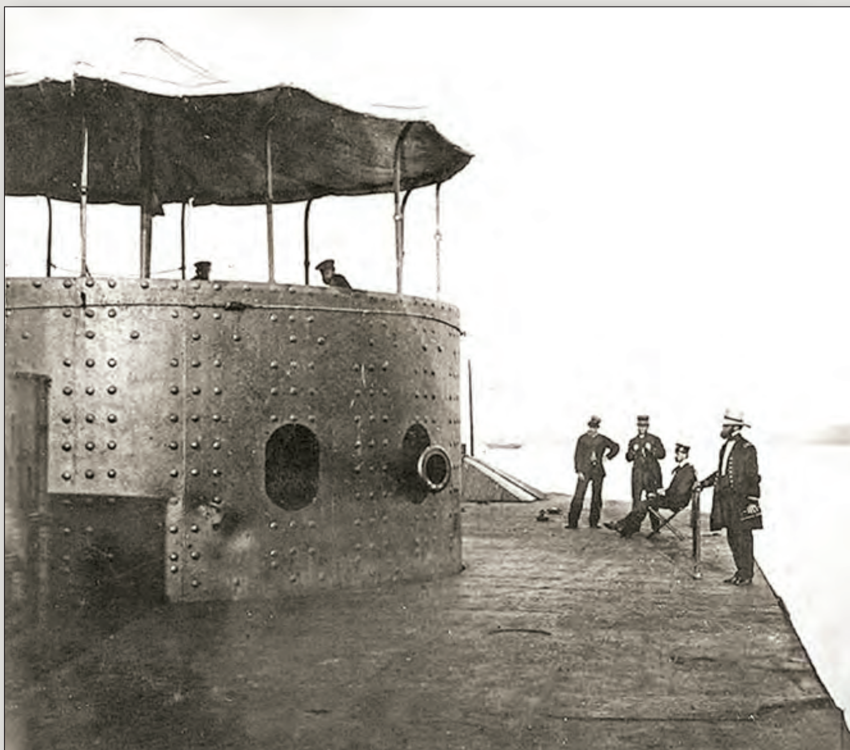


Figure 67. USS *Monitor* with four officers on deck and two crewmembers on the turret. The photograph was taken from the ship's starboard side, looking forward, in the James River, Virginia, on July 9, 1862, four months after its famous battle with the ironclad CSS Virginia (formerly USS *Merrimac*). Dents in the turret are from Confederate gun hits. *Photograph courtesy of the U.S. Naval Historical Center, photograph NH 61923.*

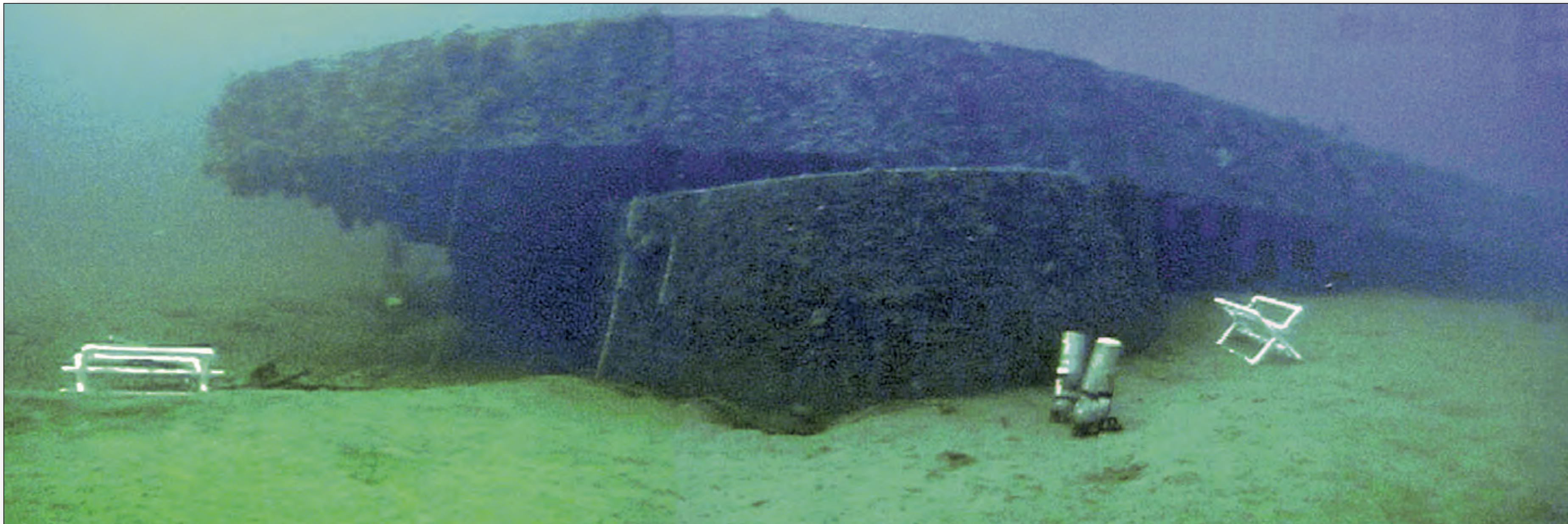


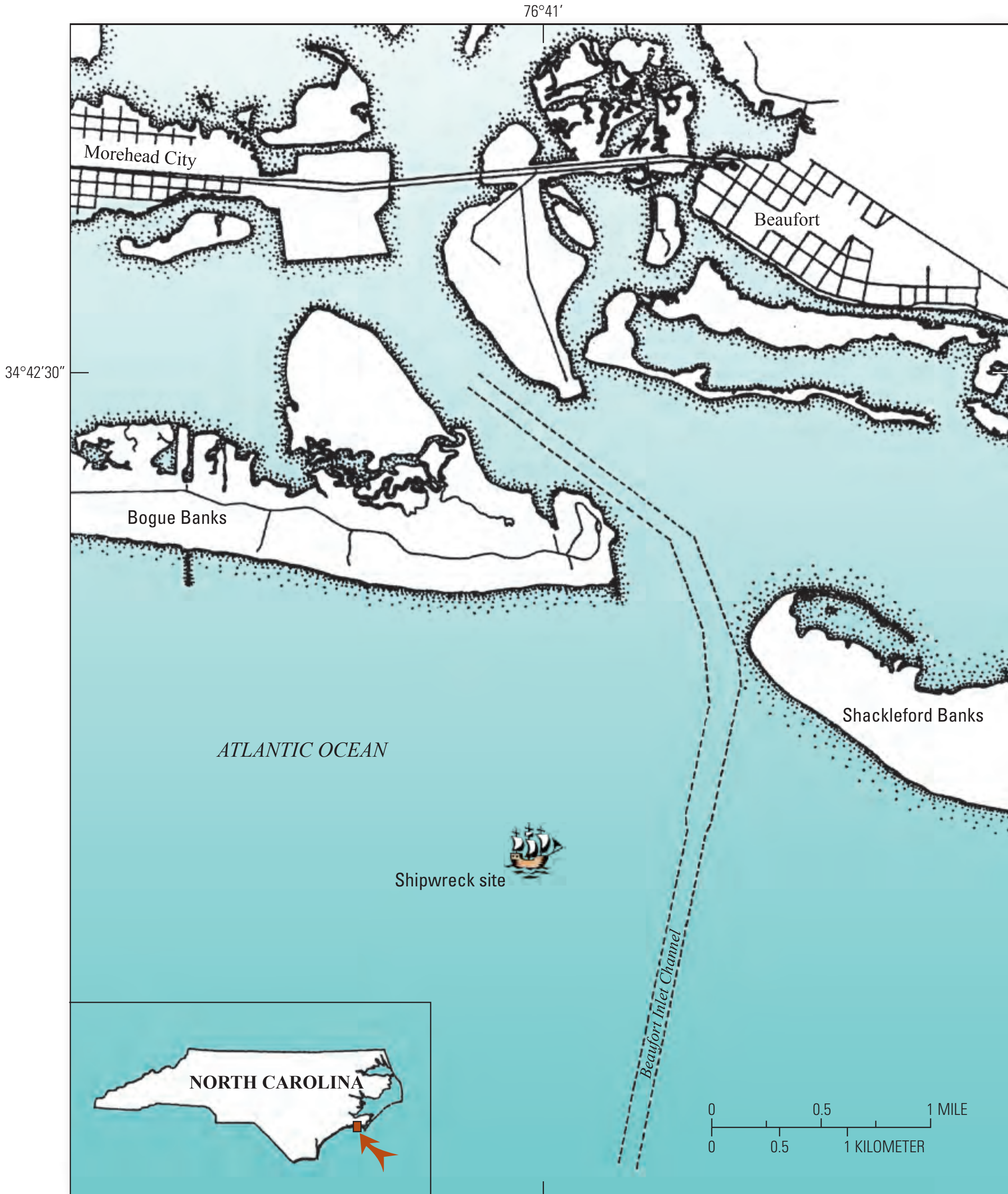
Figure 68. USS *Monitor* on the bottom of the Atlantic Ocean, at the Monitor National Marine Sanctuary southwest of Cape Hatteras. The *Monitor's* turret, which here supports the wreck, was raised in 2002 and is being conserved at the Mariner's Museum in Hampton Roads, Virginia. *Image compiled from video stills by Jeff Johnston, courtesy of the National Aeronautics and Space Administration.*

In 1996, artifacts of what appear to be the pirate Blackbeard's flagship *Queen Anne's Revenge* were found near Beaufort Inlet, NC, nearly 300 years after running aground on the ebb-tide delta's terminal lobe (fig. 69) (Wells and others, 2001). Discovery of the ship generated great public interest, and research efforts continuing in 2010 combined governmental, private, and commercial entities under the management of the North Carolina Department of Cultural Resources.

Blackbeard, whose birth name is thought to be Edward Teach or Edward Thatch, was one of colonial America's best-known seafaring criminals. He participated in the capture of more than 50 vessels, including the *Queen Anne's Revenge*, which was formerly a French slave ship. Blackbeard is suspected of running the ship aground purposefully to break up his pirate company; after selecting some crewmembers and taking valuables, he marooned the remaining crew. He was killed in a battle with the British Navy 5 months later at Ocracoke Inlet.

Why was such a ship not discovered earlier in the shallow and well-travelled location near the shore? The shifting sands of the barrier islands are thought to be responsible, because the ship may have been covered for 225 of its 282 years before discovery. Sands buried and exposed the *Queen Anne's Revenge* during alternating intervals of about 50 years (Wells and others, 2001). In addition, the Beaufort Inlet channel has changed orientation nine times during the submergence period, further reducing chances of discovery.

Figure 69 (facing page). "Shipwreck site" appears to be location of *Queen Anne's Revenge*, flagship of the pirate Blackbeard. *Courtesy of North Carolina Department of Cultural Resources Office of Archives and History, 2013; http://www.history.ncdcr.gov/.*


76°41′
34°42′30″
Morehead City
Beaufort
Bogue Banks
Shackleford Banks
ATLANTIC OCEAN
Shipwreck site
Beaufort Inlet Channel
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0
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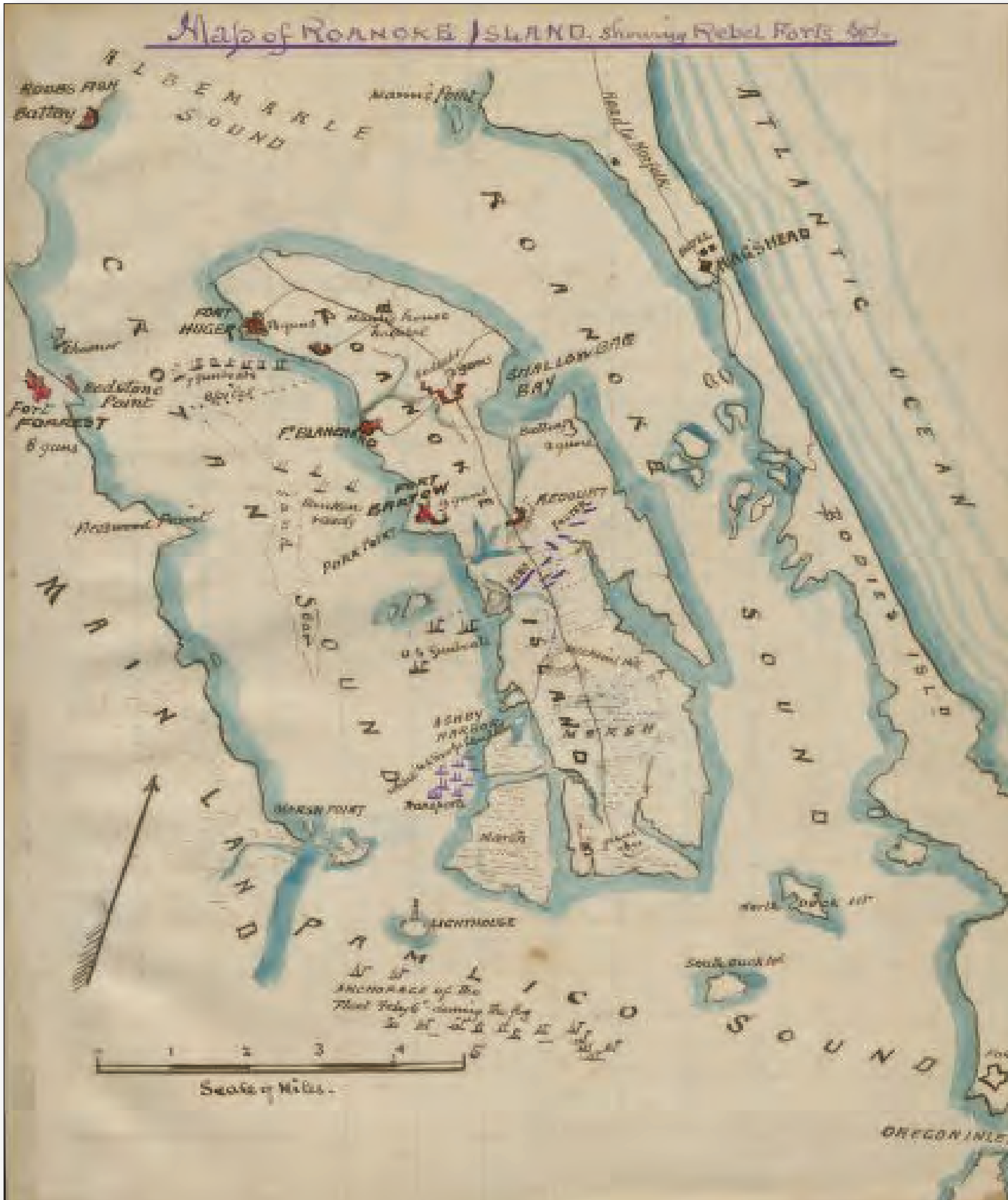

Shoreline Erosion and the Lost Colony

English explorers first attempted to colonize North America on the northern end of Roanoke Island. The best-known venture was Sir Walter Raleigh's "Lost Colony" in 1587, but other settlers made several related and failed attempts to establish a community in this location. (For more information, see a previous section, European Settlement.) Although the location of a fort (Fort Raleigh) on Roanoke Island, dating from the time of John White's colony, has been verified and is well documented (fig. 70), neither research nor archaeological fieldwork has established the settlement's location. Early records imply that the settlement was almost certainly near the fort and close to the shore of Roanoke Island. Because of storms and the rise in sea level during the 400 years since colonization, this northern exposure of Roanoke Island has continued to erode, and it is possible that any archeological remains are now under water.

Geologically, Roanoke Island is part of the Pamlico terrace of the Pleistocene Epoch about 1.8 million to 12 thousand years ago (U.S Geological Survey Geologic Names Committee, 2006) and may have once been a low divide situated between two rivers. The southern end of the island lies only slightly above sea level, and the northern end has a well-developed, 0.8 to 0.9 m-high (2.5 to 3.0 ft) bluff capped by a Pleistocene soil horizon that rests on the terrace surface and by overlying postglacial dune sands. Separating the Pleistocene soil from the postglacial layers is a thin blanket of charcoal, the remnant of a forest fire that swept the northern end of the island at some unknown earlier date.

The Roanoke Island shoreline has shifted considerably since colonization. Trends in shoreline migration along northern Roanoke Island were established for the interval 1851 to 1970 (Dolan and others, 1981) (fig. 71), and this information was updated through 1998 in the vicinity of the Fort Raleigh National Historic Site (Riggs and Ames, 2003) (fig. 72). Although charts and maps of Roanoke Island date from the 1500s, the earliest ones are too small in scale or too inaccurate to be of use. Later shoreline positions were established by using maps and charts dating from the middle 1800s and those prepared by the U.S. Army Corps of Engineers and the Coast and Geodetic Survey (fig. 71). More recent trends were determined by using aerial photographs coupled with field measurements.

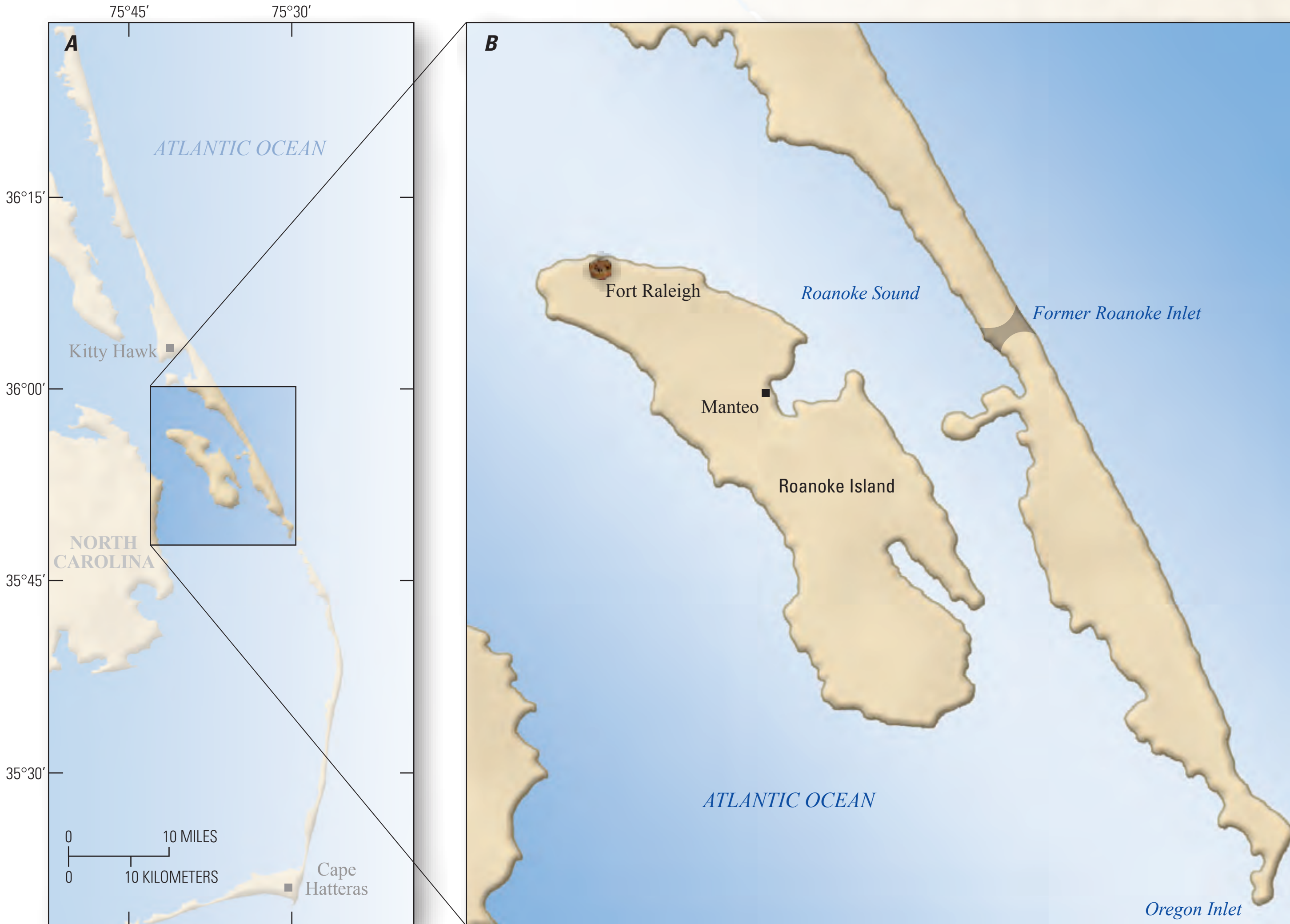

Figure 70. Location of the historical Fort Raleigh on Roanoke Island. *(Symbols courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).*

The measured (1851, 1903, and 1970) and estimated (1586) shoreline positions (fig. 71) indicate that all areas in the northern part of Roanoke Island show various amounts of shoreline erosion in the 119 years from 1851 to 1970. In an effort to slow or stop the loss of sand, the National Park Service constructed several structures along the shoreline including a rock revetment in 1980 (fig. 73), wooden bulkheads (wood structures built on the shoreline to hold sediment in place), groins (structures extending into water perpendicular to the shore designed to trap sediment in the longshore drift), and breakwaters (structures built slightly offshore but parallel to the shore designed to attenuate wave action). By 2003, about 75 percent of the northern shore of Roanoke Island was armored against shoreline erosion (Rigs and Ames, 2003). Although these structures did reduce erosion in their immediate vicinity, erosion accelerated in adjacent areas not protected by such structures. The National Park Service continues to explore solutions as this island shoreline retreats in response to storms, waves, and the long-term rise in sea level.

The north shore of Roanoke Island receded approximately 280 m (928 ft) between 1851 and 1970, and the shoreline lost a prominent feature (figs. 71 and 72). The spit northeast of Fort Raleigh called Etheridge Point eroded completely away. Erosion protection structures such as a groin field (fig. 71*B)* built in recent years trapped much of the sediment that previously had supplied the spit, leading to rapid destabilization, dispersal, and eastward migration of the spit remnants (Riggs and Ames, 2003).

Land areas facing large fetches, which produce destructive storm waves and surges, as well as those facing strong winds, may have erosion rates higher than those of more protected areas. Roanoke Island has large fetches to the north, and thus the northern part of the island is subject to destructive storm waves and surges from northeast storms as well as from strong northwest winds. This combination of wind and waves makes the island doubly vulnerable and explains the high degree of erosion on its northern end.

If the calculated erosion trend during the past 150 years for northern Roanoke Island (fig. 71) is consistent with the general trend since the "Cittie of Ralegh" was established more than 400 years ago, it is not surprising that evidence of the settlement's site remains undiscovered. If the rates are compatible, the present coast from Northwest Point to Old U.S. Highway 64 has probably receded more than 610 m (2,000 ft). The northeast shoreline (excluding Etheridge Point) from Old U.S. Highway 64 to Airport Road receded an average of about 396 m (1,300 ft). Thus, the shoreline along the entire length of northern Roanoke Island—in the very area that archeologists believe was the most likely settlement location—would have receded more than 400 m (1,320 ft). Whether the erosion of the shoreline during the first 276 years after settlement equals that of the shorter and more-recent study period is, of course, speculative, but no evidence suggests a substantial change in physical processes during this period.

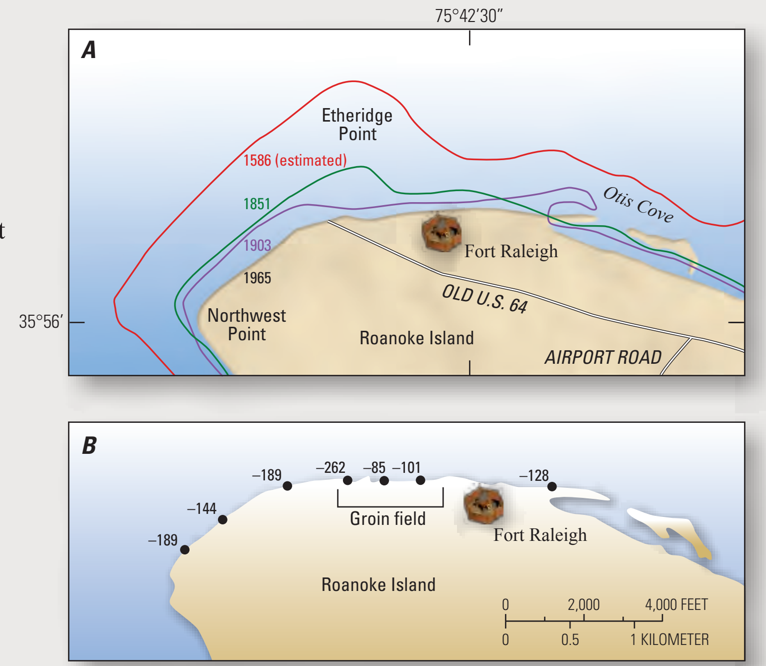

Figure 71. ***A***, Historical shoreline positions of northern Roanoke Island. ***B***, Erosion (in meters) for selected locations *(modified from Dolan and others, 1981). (Symbols courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).*

Figure 72 (inset figure, facing page). Northern Roanoke Island, 1994. The prominent spit depicted in figure 71 is gone *(modified from Riggs and Ames, 2003).*

Figure 73 (facing page). Rock revetment installed on the northern end of Roanoke Island to control erosion. Hardened structures such as these impede the transport of sediment to downdrift locations. *Photograph by Robert Dolan, September 2003.*


Roanoke Sound
Previous spit location
Riggs and Ames study location

Engineering the Outer Banks

Sun-girt City, thou hast been
Ocean's child, and then
his queen;
Now is come a darker day,
And thou soon must be
his prey

—Percy Bysshe Shelley, 1818, Lines written among the Euganean Hills

The buildings and infrastructure close to the shoreline on developed barrier islands attribute a permanency to the landscape that does not exist. People investing in barrier island development want their investments protected from the storm surge and overwash inherent to the islands. Unfortunately, interfering with the sediment transport system profoundly changes other geological and ecological processes. Most coastal engineering structures are designed to restrict sediment transport or to trap sand in a location to mitigate erosion. However, because the barrier islands comprise an entire coastal system, structures that trap sand in one area usually deprive an adjacent area. As previously noted, barrier islands recede when the amount of sand carried away from the system exceeds the amount carried in; the greater the deficit, the greater the erosional recession.

"Hard" shoreline protection structures that change natural sand flow generally fall into two categories: structures that inhibit or repulse wave energy, such as seawalls (fig. 74), bulkheads, and revetments or structures that inhibit sand transport, such as jetties and groins. In addition, as a secondary effect, roads, parking lots, and campgrounds also alter sediment flow, freshwater runoff, plant communities, and animal habitat.

"Soft" mitigation is generally considered more environmentally friendly than "hard" engineering. Beach nourishment (mechanically placing additional sand on a beach) has gained favor in recent years, although it is temporary and expensive and produces its own ecological problems. These problems include disturbing the indigenous biota occupying beach habitats and disrupting the nesting, nursing, and breeding habitats of species that inhabit the beach zone. Creating sand dunes by trapping windblown sand with fences is another soft engineering response, but such trapped sand alters overwash patterns, changes vegetation communities, and interferes with the landward migration of the islands.

In the United States, beach nourishment has become the preferred way to reduce coastal erosion (fig. 75). The lifespan of nourished beaches is highly variable and may depend on a number of factors, such as storm frequency and intensity, quality of the sand used, and the volume of sand used per unit length of beach (Weggel, 1995). Along the Middle Atlantic coast, sediment finer than 0.1 mm (0.04 in.) is commonly transported offshore or through inlets and into the bays and sounds behind barrier islands. This sediment movement can lead to secondary environmental problems, such as increased turbidity and alteration of beach and inshore substrates required by intertidal fauna. How beach nourishment and resultant disturbance of the subtidal zone affects subtidal organisms is not well understood (Nordstrom, 2005).

Beach nourishment is not a practical solution for an individual property owner or even a group of small-property owners with an erosion problem because these projects usually involve miles of oceanfront beach and the importation of millions of cubic meters of sand. Consequently, beach nourishment is very expensive and requires widespread political and community support. In most cases, the Federal government becomes directly involved through the expert knowledge, planning, and permitting responsibilities of the U.S. Army Corps of Engineers.

Figure 74. North Carolina coastal regulations prohibit hardened coastal engineering structures such as this seawall in Galveston, Texas *(Morton, 2004).*

Figure 75. Pipeline apparatus and related equipment associated with a beach nourishment project at Kure Beach, North Carolina. Longshore drift is to the south (bottom of photograph.) The kink in the shoreline marks the difference between shorelines before (upper left) and after (lower right) beach nourishment. *Photograph by Bud Davis, courtesy of the U.S. Army Corps of Engineers.*

North Carolina Coastal Regulations

The North Carolina Environmental Policy Act of 1971 provided decisionmakers with a way to "consider environmental aspects and consequences of a proposed development" (North Carolina Environmental Policy Act, 2005). This act also declared that North Carolina's continuing policy would be to "conserve and protect its natural resources and to create and maintain conditions under which man and nature can exist in productive harmony" (North Carolina Environmental Policy Act of 1971, 1971). Satisfying these goals has become more complex since 1971 as population and development pressures increased.

In 1974, recognizing that coastal areas of the State were among its most valuable resources, the North Carolina legislature passed the Coastal Area Management Act. Among other items, this management act established North Carolina's Coastal Resource Commission in order to do the following:

1. Provide a management system capable of preserving and managing the natural ecological conditions of the estuarine system, the barrier dune system, and the beaches, so as to safeguard and perpetuate their natural productivity and their biological, economic, and esthetic values;

2. Insure that the development or preservation of the land and water resources of the coastal area proceeds in a manner consistent with the capability of the land and water for development, use, or preservation based on ecological considerations (Coastal Area Management Act, 1974).

In part because of this management act, North Carolina now has some of the most restrictive coastal development regulations in the Nation. The North Carolina Department of Environment and Natural Resources prohibits many of the shoreline engineering structures found in other coastal areas of the United States. It does not allow "permanent stabilization of the ocean shoreline, because structures such as bulkheads, seawalls, jetties, and groins interrupt natural sand migration patterns and can increase erosion at nearby properties" (CAMA Handbook, 2003). Further, the North Carolina Division of Coastal Management permits only two responses to shoreline erosion that presents a hazard to structures: removing buildings to a safer location, or replenishing the beach's supply of sand, and it advises property owners to place new buildings as far back from the beach as possible.

Most coastal projects governed by the Coastal Area Management Act are exempt from review under the North Carolina Environmental Policy Act of 1971. However, major coastal projects such as beach nourishment, dredging new navigation channels, and excavation of aquatic areas for beach nourishment, as well as any project requiring public funding, are governed by the Coastal Area Management Act and are also subject to review under the Environmental Policy Act (North Carolina Environmental Policy Act, 2005).

Economic Considerations of Coastal Engineering

The question of who pays for and who benefits from coastal engineering projects has no simple answer. Financing for these programs is hotly debated because most large coastal engineering projects are very costly and require public funds. Some taxpayers question whether the expenditure of public funds for beach nourishment and other coastal engineering projects is fair, because only a limited number of people (primarily those who own or have easy access to the oceanfront) will enjoy the benefits. Others argue that benefits from coastal engineering projects are offset by the ecological damage they cause. The valuation of benefits and liabilities of coastal engineering activities is rarely straightforward.

Increased property values and increased public revenue through property taxes are among the more visible outcomes of shoreline protection. Property values and community revenues generally increase after beach nourishment projects. Of course, the direct economic effects on the community served are only part of the story. Perception among domestic and foreign tourists that United States' beaches are worth visiting is an important reason why travel and tourism is America's leading industry (Houston, 2002). The United States lacks a national agency to manage tourism, and the tourism industry is fragmented among many small business owners. As a result, "the importance of travel and tourism to the national economy has not been communicated to the American people" (Houston, 2002).

On the other hand, because "beach width is a nonmarket good, the actual value of a wider beach is difficult to measure" (Pompe and Rinehart, 1999). There is no standard metric for assessing the economic value of natural areas and parklands beyond measuring the direct revenue they generate and counting the number of visitors. Moreover, coastal engineering structures disturb and degrade ecosystems and preserves. Ecological economists have attempted to determine a way to place a value on services provided by ecosystems beyond generation of community income. Establishing such measures has, however, proven difficult.

The U.S. Army Corps of Engineers is commonly at the forefront of exchanges involving coastal engineering, because the Corps is responsible for maintaining and improving the Nation's navigable waterways and protecting coastlines from damage by hurricanes or other storms. As such, it also has primary responsibility for large beach nourishment programs in the United States, as well as for the maintenance of navigation channels such as the navigable inlets of the Outer Banks.

Engineering Projects on the Outer Banks

Dune Stabilization Program

Severe storms and overwash along the Outer Banks precluded permanent roads until the 1930s, when work began on a protective dune system between the proposed road and the beach. In 1936, the Civilian Conservation Corps and the Works Progress Administration, under the direction of the National Park Service, began constructing 167 km (104 mi) of sand fencing and planting nearly 400 hectares (980 acres) with grasses (fig. 76) such as American beach grass (*Ammophilia breviligulata*). The project's purpose was to "arrest and prevent sand erosion by wind and wave action along more than 100 miles of beach in the proposed Cape Hatteras National Seashore in North Carolina" (Unrau and Williss, 1983). At the time, however, the land managers and planners did not have a comprehensive understanding of the intensity and magnitude of the sand transport processes they were attempting to control. Consequently, though the program reduced overwash frequency, it did not stop erosion (Behn and Clark, 1979).

Figure 76 (left). During the 1930s, the Civilian Conservation Corps and Works Progress Administration erected fences on the broad beaches of Hatteras Island to trap wind-blown sands, modifying the island to form its characteristic barrier-dune system. This photograph, taken in the late 1930s from the Cape Hatteras Lighthouse, shows workers planting grass behind sand fences. *Photograph courtesy of the National Park Service.*

The island stabilization project resulted in a continuous barrier dune along the Outer Banks islands of Hatteras, Pea, and Bodie. The sand fences placed just inland from the beach face inhibited airflow, decreased wind energy, and caused sand deposits to accumulate at the fence. Sand build-up eventually covered the fences and formed a high dune. Most of these fences were constructed in the region between the original low beach dunes close to the shoreline and 30 to 91 m (100 to 300 ft) behind the foredune (fig. 45). The sand that collected around the fences was stabilized further with approximately 2.4 million trees and shrubs. In the 1960s, the National Park Service introduced more vegetation and fertilized the stabilized beach barrier dunes. The artificial dunes grew as high as about 10.5 m (35 ft). Steep backslopes developed because sand could not easily migrate over these tall dunes.

The dune stabilization program greatly altered the ecology and geology of the affected areas. In the 40 years following dune construction, the beach profile narrowed and steepened because wave energy from storms could not dissipate across the islands. In addition, the dunes impeded overwash and salt spray, and the vegetative succession changed from open berm grassland communities to shrub thickets between south Nags Head and the southern tip of Ocracoke Island. This process changed the natural low-profile life zones of the islands into an altered, stabilized community (see fig. 47). In the stabilized system, shrub communities migrate seaward from their natural positions nearer the sound and can form impenetrable thickets 3 to 5 m (10 to 15 ft) high. Before dune stabilization, for example, only a few shrubs grew in the drifting sand around Bodie Island Lighthouse near Oregon Inlet. After dune stabilization, more and more woody shrubs moved into this area (fig. 77).

Both the U.S. Fish and Wildlife Service and the National Park Service have checked the spread of shrubs with controlled fires. Shrubs and other species flourishing in the protection of the artificial barrier dunes are not well adapted to flooding, burial from overwash, or salt spray. After a washover on a natural barrier island, indigenous plants can renew themselves within one growing season.

Figure 77. Bodie Island Lighthouse in 1955 (***A***) and 2001 (***B***). ***B***, Note narrower beach and more mature vegetation. ***A****, Carolina Motor Club "Trip of the Week" cover photograph, July 19, 1955, from the National Park Service, courtesy of the National Archives and Records Administration;* ***B****, photograph by Bill Berkemeier, courtesy of the U.S. Army Corps of Engineers.*

Figure 78. Barrier island stabilization can narrow the beach if it can no longer migrate landward in response to change. This September 2001 photograph of the Kitty Hawk–Kill Devil Hills area shows a beach bordered landward by a road. *Photograph by William Birkemeier, courtesy of the U.S. Army Corps of Engineers.*

Another striking difference between natural and stabilized barrier islands is beach width (fig. 78). The unaltered island beaches are about 120 to 200 m (400 to 650 ft) wide and average about 150 m (500 ft) wide. Many stretches of Hatteras Island beach are now less than 30 m (100 ft) wide.

Interference with overwash processes and inlet dynamics also decreases the islands' ability to create new marshlands. Before stabilization, new marsh areas developed when grasses colonized the sand deposited in the sounds by temporary inlets and overwash processes. Although marshes can grow vertically on accumulated organic material, they cannot expand laterally into the sound once the supply of washover sand is cut off. After stabilization and the consequent reduction in washover sand, marshes tend to have scarped and eroding edges.

The higher profile of a stabilized barrier island makes the draining of elevated storm water more difficult. Prior to stabilization, when northeast storms pushed water from Pamlico Sound against the backside of the islands, the water simply flowed between the dunes and into the ocean. Now the water does not drain as readily, and much of the land behind the stabilized dunes floods periodically. Similarly, hurricane winds from the southeast force elevated water from the ocean into the sound but, as the storm progresses northward, winds generally shift to the northwest and the elevated sound water gets trapped behind the dunes.

Further complicating the situation is the impression of safety and stability created by the barrier dune. Numerous structures, such as motels, restaurants, homes, park facilities, and the U.S. Naval Station at Cape Hatteras, were built immediately behind the barrier dunes in the belief that the dunes would provide reliable protection. Instead, the beach has continually narrowed and the barrier dunes have eroded away, leaving many of these structures with little protection against extreme storms (fig. 79).

Figure 79. South Nags Head home in the active surf zone. *Photograph by Robert Dolan, September 2003.*

In the 1970s, the National Park Service ended its program of large-scale dune stabilization because of high maintenance costs and unintended or undesirable effects on geological and ecological processes (Dolan, 1973). Although scientists in the early 1970s substantiated that the islands were intrinsically unstable and that they naturally respond to stress by accretion or erosion (Dolan, Godfrey, and Odum, 1973), as early as 1938 the National Park Service's own geologists had asserted that the low, open nature of the Outer Banks was a response to natural processes. Upon completion of a beach nourishment project at Buxton in 1973, the National Park Service outlined its new dune stabilization policy as follows:

> Following damaging storms, the dunes [will] not be artificially rebuilt, but in extensive barren areas a re-vegetation program [will] be initiated. Inlets which opened during storms [will] be permitted to migrate and close naturally. This alternative envisions that at some time in the future it may be impractical to maintain a continuous road through the seashore (Behn and Clark, 1979).

Since the National Park Service ended its dune-maintenance program, barrier dunes have eroded and highways and buildings have been increasingly damaged by storm surge. By 2008, less than one tenth remained of the original dunes stabilized by the Civilian Conservation Corps. As the beach eroded and the shoreline approached the dunes, the dunes were attacked more frequently by smaller and smaller storms until in many places they disappeared. It is thought that by 2090, most of the artificial dunes will be gone (DeKimpe and others, 1991). Houses and developed property in the pathway of the overwash are increasingly susceptible to damage or destruction and, perhaps more important, North Carolina Highway 12 is now vulnerable.

North Carolina Highway 12

North Carolina Highway 12, built on the sound side of the artificial dune system, presents many problems for both the North Carolina Department of Transportation and the National Park Service. When Highway 12 was planned and constructed in the 1940s, the best location for the roadbed was immediately inland from the newly stabilized barrier dunes on the relatively stable overwash terraces. No one at the time knew that this seemingly ideal location would eventually become very high risk (fig. 80).

Maintaining the road, which provides the only access connecting all the Outer Banks villages, has become one of the highway department's highest and most costly priorities. In some places the highway has been moved back from the beach several times. However, such movement is practical only in the national seashore and national fish and wildlife areas and, even in these areas, suitable locations for a new road are becoming limited. Relocation of the road is virtually impossible in developed areas. In addition, the road is routinely cleared of sand deposited by overwash, and periodically it must be repaved after storms flood the road and break the asphalt. The road has been rerouted several times when erosion destroyed or threatened the dunes, bridges have been abandoned, and roads have been built where ephemeral inlets closed (fig. 81). As the beach system continues to narrow, overwash, erosion of the artificial barrier dunes, and inlet formation continue to reshape the islands. Many structures built near the beach have been lost.

North Carolina's coastal construction policies prohibit using engineering structures such as bulkheads or groin fields to protect the road. Beach nourishment is an option, but it may cost tens of millions of dollars per mile and, in most cases, is only a temporary measure.

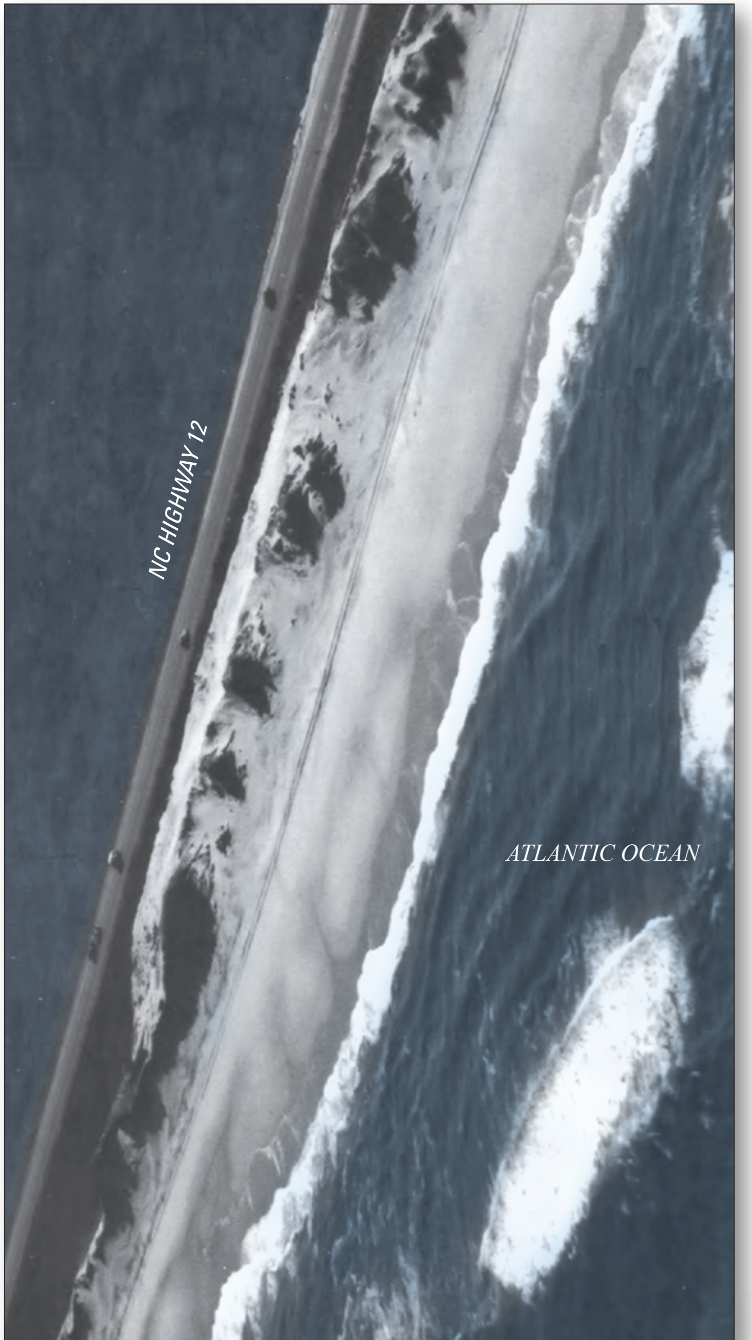

Figure 80 (far left). Active surf approaches North Carolina Highway 12 as the beach erodes. The road requires routine maintenance and is often overwashed with sand. *Photograph by Robert Dolan.*

Figure 81 (immediate left). The remains of an old roadbed and bridges created for "New Inlet," which formed on Pea Island during the 1930s. The inlet sealed naturally before the bridge could be used. *Illustration courtesy of Fred Hurteau, www.outerbanksguidebook.com; background photograph by National Oceanic and Atmospheric Administration.*

Oregon Inlet

A hurricane passing the Outer Banks on September 8, 1846 generated high waves and storm surge and breached Hatteras Island in several places. Two of these breaches developed into Oregon Inlet to the north (fig. 82), and Hatteras Inlet to the south—about 24 km (15 mi) south of Cape Hatteras. Both have remained open for more than 150 years.

Oregon Inlet is now the only inlet between Cape Hatteras and Cape Henry at the mouth of Chesapeake Bay, Virginia. This inlet is the primary conduit for tidal exchange between the Atlantic Ocean and Pamlico Sound, one of the largest estuaries in North America. Fishing and recreational industries depend on the inlet, because it provides the only pathway to estuarine nurseries for several migratory and commercial fish species.

Between 1585 and 2003, the number of active inlets at any one time along the Outer Banks north of Cape Hatteras ranged from 1 to 8. Oregon Inlet's presence in 2012 as the single active inlet in this 160-km (100-mi) length of coastline is unusual. Historical sources suggest that in 1585, when Sir Walter Raleigh's colonists sailed to Fort Raleigh on Roanoke Island, two inlets were present just north of Oregon Inlet's location.

Managing Oregon Inlet has been a challenge for decades not only because it is the primary inlet-outlet between Pamlico Sound and the ocean, but also because it is the primary transportation link across and adjacent to the inlet. Land managers' goals are to maintain North Carolina Highway 12 and Bonner Bridge across the inlet while minimizing environmental effects associated with maintenance (fig. 83). Inlet maintenance is complicated by the fact that Highway 12 provides the only north-south access along the Outer Banks islands, that Oregon Inlet is the only navigation channel through the Outer Banks, and that the protected areas of Cape Hatteras National Seashore and Pea Island National Wildlife Refuge border the inlet to the north and south (fig. 84) (Dolan and Smith, 2003).

Figure 82. Oregon Inlet, North Carolina. *Photograph courtesy of the U.S. Army Corps of Engineers, September 18, 2001.*

Figure 83. Oregon Inlet and Bonner Bridge. *Photograph by Robert Dolan, June 16, 2005.*

Figure 84 (page 114 and 115). The Hatteras Breach (also known as Isabel Inlet and Buxton inlet) just north of Hatteras Village, North Carolina. Hurricane Isabel caused the breach on September 18, 2003, when it struck the Outer Banks as a Category 2 Hurricane.

The breach opened in a low, narrow area of the island. Such low swales in the dune system are vulnerable to breaches when water levels rise. After a low area is inundated, rising water flowing through the low area can submerge nearby dune crests, eroding them rapidly. Here, the breach destroyed the only local road to the area, thus isolating residents of Hatteras Village until after repairs *(Wamsley and others, 2009).*

Through interagency cooperation, the U.S. Army Corps of Engineers began closing the breach on October 17, 2003, and completed the closure 15 days later. The Corps used 34,000 feet of pipeline to transport 300,000 cubic yards of sand from a borrow area in Pamlico Sound west of Hatteras Inlet. The final panel shows the closed breach and restored road on November 18, 2003. *Photographs by D.C. Wilson, Virginian-Pilot newspaper, and used with permission.*

October 17, 2003

October 23, 2003

October 27, 2003

October 30, 2003

November 2, 2003

November 18, 2003

Figure 85. Terminal groin, northern end of Hatteras Island at Pea Island National Wildlife Refuge. *Photograph by Michael Halminski, June 17, 2005.*

The longshore transport of sand along the Outer Banks varies by as much as 1.5 million m3 (2 million yd3) per year. From the time it opened in 1846 until the present, Oregon Inlet migrated southward about 3 km (2 mi), an average rate of about 18 m/yr (59 ft/yr). In 1988, inlet migration began threatening the stability of the south end of Bonner Bridge, and in 1990 the North Carolina Department of Transportation built a 975-m- (3,128-ft) terminal groin at the northern tip of Pea Island (fig. 85). The groin has markedly altered Oregon Inlet's dynamics and configuration but, as predicted, it did halt inlet migration.

Maintaining even minimal navigation depths and a relatively straight channel have been difficult and costly. The U.S. Army Corps of Engineers has dredged Oregon Inlet and pumped the sand to Pea Island National Wildlife Refuge since 1989. Pipeline dredges extract the sediment when volumes exceed 191,000 m^3 (250,000 yd^3) and pump the sediment directly onto the beaches at Pea Island (fig. 86). For lesser volumes, split-hulled hopper dredges place dredged material into Pea Island's surf zone, in water 4 to 6 m (13 to 20 ft) deep. Side-cast dredges (fig. 87) are also used.

Figure 86. The U.S. Army Corps of Engineers pipes material dredged from Oregon Inlet onto the beach at Pea Island National Wildlife Refuge. *Photograph by William Birkemeier, courtesy U.S. Army Corps of Engineers.*

Figure 87. Sidecasting dredge at Oregon Inlet. *Photograph by Michael Halminski, March 31, 2005.*

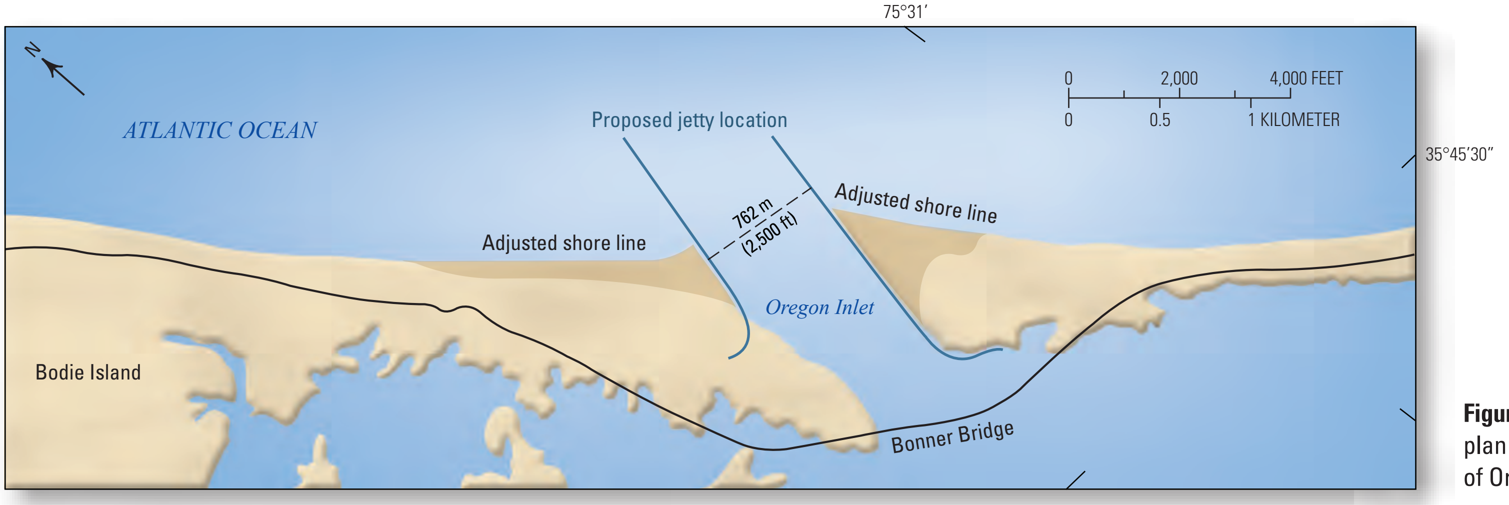

Figure 88. The proposed (and rejected) plan to construct a jetty on each side of Oregon Inlet.

Since the 1990s, split-hulled hopper dredges have transported approximately 1 million m^3 (1.3 million yd^3) of sand to Pea Island, combined with approximately 5 million m^3 (6.5 million yd^3) transported with pipeline dredges. A White House Council of Environmental Quality 2003 referral statement requires that the U.S. Army Corps of Engineers will dredge nearly twice this amount by 2015 to meet navigation channel maintenance requirements, with attendant environmental implications. In 1970, when Congress authorized an improved project for stabilizing Oregon Inlet, it directed the Corps to build a dual jetty (each jetty 2.4 km (1.5 mi) long) to stabilize both sides of the inlet (fig. 88), coupled with a sand-bypassing plan. The Oregon Inlet stabilization project (also known as the Manteo (Shallowbag) Bay project) would have been one of the largest coastal engineering works on the Atlantic Coast. The project was intended to protect vehicle, power, and telecommunication access to Hatteras Island across Bonner Bridge, while maintaining navigation access through the inlet for commercial and recreational watercraft. The estimated cost for the project was about $125 million. Opponents of the dual jetty system proposal were not convinced that its dredging plan could properly balance the sediment budget or predict the ultimate effects of the jetties, given the incomplete understanding of the inlet's dynamics.

Federal agencies rejected the plan in 2003, ending the 30-year debate among coastal scientists, engineers, and public land managers. Ultimately, the inlet's proximity to Cape Hatteras National Seashore and Pea Island National Wildlife Refuge led to the project's demise because of concerns (by both the National Park Service and the U.S. Fish and Wildlife Service) related to maintaining healthy island ecosystems.

The North Carolina Department of Transportation's plan to replace the aging Bonner Bridge is a more recent development in Oregon Inlet's story. Bonner Bridge was completed in 1963. The life expectancy of the original bridge was estimated to be approximately 30 years, so it has outlived its design life. In 2011, the State's Department of Transportation awarded a design-build contract for a replacement bridge. However, construction was delayed because of environmental concerns related to bridge and road construction within sections of the Pea Island National Wildlife Refuge. In June 2015, the North Carolina Department of Transportation, the North Carolina Department of Environment and Natural Resources, and the Federal Highway Administration finalized a settlement agreement with Defenders of Wildlife and the National Wildlife Refuge Association, allowing the N.C. Department of Transportation to replace the Bonner Bridge over the Oregon Inlet with a new parallel bridge. Under the agreement, the Department of Transportation will also consider options that would move vulnerable portions of North Carolina Highway 12 out of the southern half of Pea Island National Wildlife Refuge and into Pamlico Sound (http://www.ncdot.gov/projects/bonnerbridgereplace/).

The design of the new Bonner Bridge was the subject of considerable discussion and environmental review during the 1990s and 2000s. Many were convinced that the new bridge, regardless of cost, should completely bypass Oregon Inlet and instead take a route from the Oregon Inlet Fishing Center on Bodie Island and connect with Hatteras Island near the village of Rodanthe, approximately 20 km (12 mi) south of the inlet. This route would avoid the many problems associated with erosion and overwash along Pea Island and the associated maintenance of Highway 12. Others preferred a route that parallels the existing bridge because of its lower cost and because it maintains access to Pea Island beaches.

Engineering on Cape Lookout National Seashore

Cape Lookout National Seashore, consisting of North Core Banks, South Core Banks, and Shackleford Banks, is undeveloped with the exception of National Park Service concessionaires and a few modest camping structures. Bridges do not connect the islands to the mainland, so access is limited to boat or ferry. Coastal engineering structures are much less common here than north of Ocracoke Inlet. A granite-boulder jetty near Cape Lookout, the artificial opening of New Drum inlet, and a 2006 shore restoration project near the lighthouse are three examples of engineering projects on Cape Lookout.

Before Congress created the Cape Lookout National Seashore on March 10, 1966, and before the current Barden Inlet opened in 1933, plans were made to build a safe harbor near Cape Lookout (Borelli and Wells, 2002). The Cape's present shape is largely a result of this structure, built in 1915 (Godfrey and Godfrey, 1976). Part of the plan included a shore-parallel breakwater along Shackleford Banks connected to Cape Point, creating a harbor directly offshore. Only 2 km (1.2 mi) of the proposed 8 km (5 mi) breakwater were completed. When Barden Inlet opened, the partial breakwater near the mouth of the new inlet became a jetty. Currently, sediment bypasses the jetty and has lengthened a spit in the area at a rate of 37 m/yr (121 ft/yr) since 1940 (fig. 89) (Borelli and Wells, 2002).

In a more striking engineering project, the U.S. Army Corps of Engineers reopened historic New Drum Inlet on Core Banks in 1971. Old Drum and New Drum Inlets are ephemeral, and previous openings and closings date back to the early 1800s and pre-1585, respectively. When Old Drum closed naturally in 1971, the U.S. Army Corps of Engineers responded by reopening historic New Drum Inlet on December 3 that same year, about 4 km (2½ mi) south (fig. 90) (Coastal Planning and Engineering, Inc., 2004). In 1999, waves from Hurricane Dennis reopened Old Drum Inlet (Coastal Planning and Engineering, Inc., 2004) and, as of 2010, both inlets remain open and are not being artificially maintained.

More recently, the U.S. Army Corps of Engineers replaced sediment on the sound side of the national seashore to protect Cape Lookout Lighthouse and the keeper's quarters. After an inlet channel shifted in the late 1970s, the shoreline near the lighthouse rapidly eroded, leaving the structures in a more vulnerable position (National Park Service, 2006) (fig. 91). Then in 2003, Hurricane Isabel damaged part of the historic compound. In 2006, the U.S. Army Corps of Engineers placed about 46,000 m^3 (60,000 yd^3) of sediment along 793 m (2,600 ft) of the sound shoreline (U.S. Army Corps of Engineers, 2006).

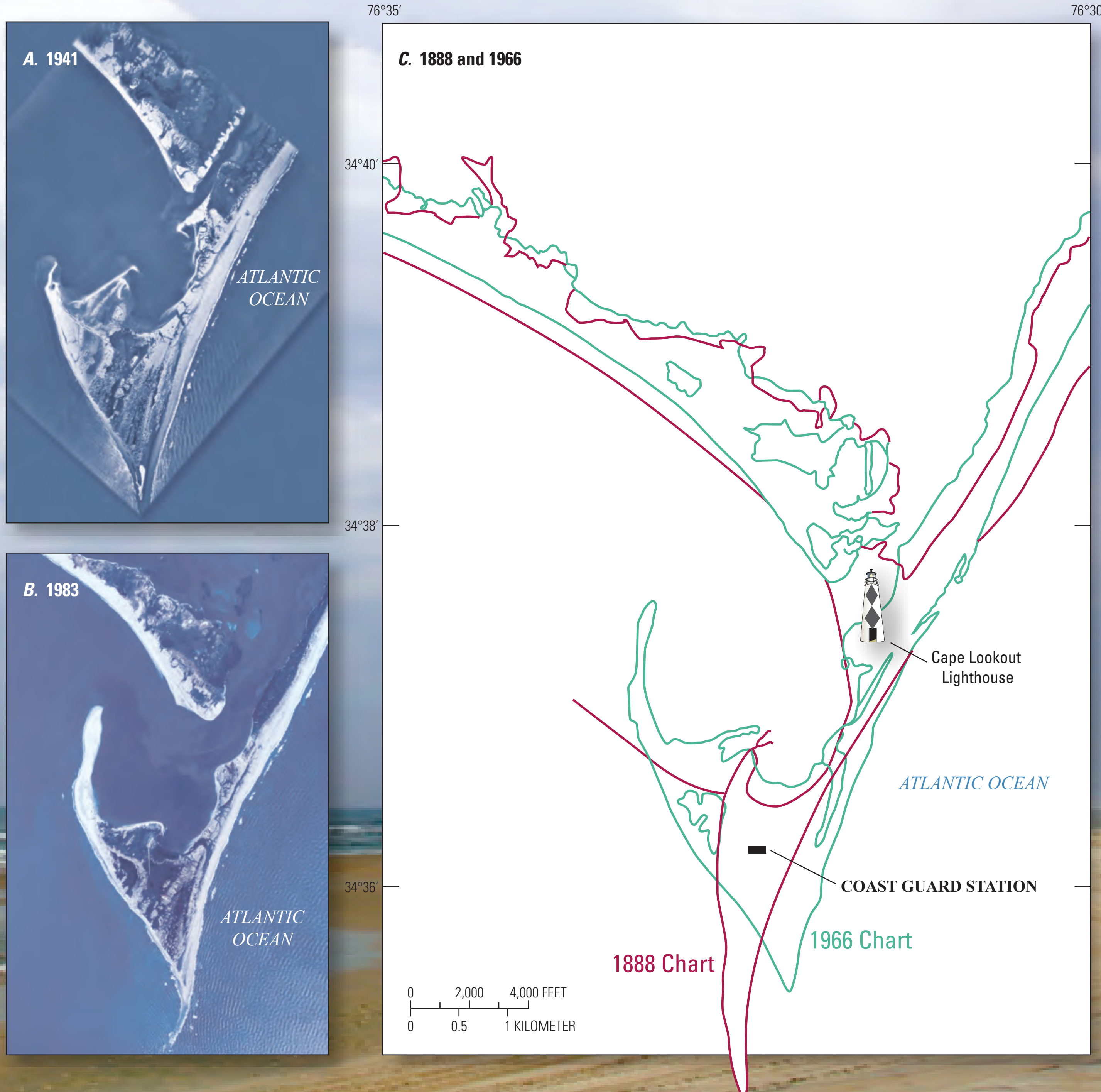

Figure 89. The evolution of Cape Lookout after construction of a jetty in 1915, which altered sediment dynamics and caused lengthening of the spit on the left side of the cape. ***A**, courtesy of the National Park Service; **B**, from Godfrey and Godfrey, 1976; **C**, courtesy of the U.S. Geological Survey.*

Figure 90. The U.S. Army Corps of Engineers reopened historic New Drum Inlet on Core Banks (***A***) in December 1971 (***B***). *Photographs by U.S. Army Corps of Engineers, courtesy of the National Park Service.*

Figure 91 (above). Erosion after a channel shift encroaches upon Cape Lookout Lighthouse and keeper's quarters. *Photograph by J.J. Smith, 2002.*

Moving the Cape Hatteras Lighthouse

The Cape Hatteras Lighthouse, the tallest in North America at 61 m (200 ft), is one of the most popular historical attractions on the Outer Banks. Built in 1875, the lighthouse replaced earlier structures that had been lost to beach erosion. When constructed, the lighthouse was approximately 460 m (1,500 ft) from the shoreline. By 1987, erosion had reduced this distance to less than 50 m (160 ft), and it was feared that the structure had become vulnerable to damage from a severe hurricane. In need of an effective solution, the National Park Service requested an evaluation of the problem, along with options for preserving the lighthouse, from the National Academy of Science's National Research Council.

After an 18-month study, the Council concluded that the lighthouse would be lost within a few decades, or sooner, in response to "a direct hit by a severe hurricane or series of lesser storms" (U.S. National Research Council, 1988). Of 10 options for preserving the lighthouse and associated buildings, the preferred approach was to move the lighthouse complex to a more storm-resistant location. During the ensuing decade the relocation option was extensively debated and discussed and, in the spring and summer of 1999, after receiving approximately $12 million for the project from Congress, the National Park Service moved the lighthouse and associated buildings.

Moving the lighthouse, which weighs 4,400 tons, was technically challenging. The structure had to be raised with hydraulic jacks, placed on a wheeled platform (fig. 92), and transported on tracks about 884 m (2,900 ft) to the southwest (figs. 93, 94). The lighthouse now sits about 488 m (1,600 ft) from the shoreline, where it should be safe from the effects of erosion and storm waves for about 100 years. The process associated with moving the lighthouse, including analysis, public hearings, decisionmaking, and funding, demonstrated that buildings can be relocated successfully from high-hazard zones along the coast.

Figure 92 (left). A special rail transport carried the Cape Hatteras Lighthouse to a location about one-quarter mile farther inland. *Photograph by Kevin Adams, 1999.*

B

A

Figure 93. Cape Hatteras Lighthouse is prepared for its journey inland in 1999 (***A***), away from the encroaching ocean (***B***). ***A****, photograph by Kevin Adams;* ***B****, photograph by J.J. Smith.*

Figure 94. Moving Cape Hatteras Lighthouse. *Photograph by Kevin Adams.*

Land Management Considerations

Recent Trends in Land Use

I must go down to the sea again, for the call of the running tide

Is a wild call and a clear call that may not be denied.

—John Masefield, 1902, Sea Fever

The rate of population growth along the Outer Banks in recent decades has been among the highest in North Carolina. The permanent population of the Outer Banks portion of Currituck County, for example, grew 32 percent between 1990 and 2000 from 13,736 to more than 18,190 people. Concurrently, Dare County also grew by 32 percent, increasing from 22,746 to 29,967 persons. Between 2000 and 2010, however, population growth slowed in Dare County, increasing approximately another 13 percent to 34,000. In comparison, the population of North Carolina grew 21 percent between 1990 and 2000, and 18.5 percent between 2000 and 2010. Tourism is the economic engine of the Outer Banks, and the seasonal population, which peaks during the summer months, is also growing. "Dare County estimates that its daily population increases by more than 225,000 additional residents during peak summer months," which is more than six times its permanent population (University of North Carolina, Carolina Population Center, 2016).

Development of the Outer Banks has also increased during the past several decades although the amount of land available for development is limited (figs. 95, 96). More than 60 percent of the Outer Banks, from Currituck to Cape Lookout, is in Federal and State parks, seashores, wildlife refuges and sanctuaries, and historical sites and monuments. These protected lands ensure that the rich natural diversity of flora, fauna, and landscape will survive for future generations. Of the remaining 40 percent of land, most has either already been developed or is slated for development.

Full development of existing land does not mean that new construction on the islands is at an end. In the near term, plans exist for redevelopment of existing properties. As the value of property all along the Outer Banks has soared, so too has the financial incentive to tear down and replace first- and second-generation beach cottages with much larger houses. Not surprisingly, this intensification of land use on existing properties is controversial because it increases the demand for water, sewer, power, and other community services that, in turn, increases stress on the islands' ecosystems (fig. 97). To address these concerns, county governments on the Outer Banks are looking to reduce these demands through improved building practices and caps on the size of replacement structures.


Wright Memorial

Figure 95 (facing page). Changes in land use near the Wright Memorial. ***A***, looking northeast in the 1940s; ***B***, looking southwest in 2001. ***A**, photograph by Aycock Brown, courtesy of the National Park Service;* ***B**, photograph by William Birkemeier, courtesy of the U.S. Army Corps of Engineers.*

Figure 96. Whalebone Junction at the northern boundary of Cape Hatteras National Seashore in 1958 (***A***) and 2002 (***B***). ***A****, photograph by Gus Martin, courtesy of the North Carolina News Bureau, Department of Conservation and Development;* ***B****, photograph by Robert Dolan.*

Figure 97. Housing encroaching on a marsh on Roanoke Island. *Photograph by Robert Dolan.*

Freshwater

Additional constraints on future development are being imposed by the physical characteristics of the islands themselves. Although the Outer Banks are surrounded by water, the amount of potable freshwater available on them is limited. As with other wide barrier islands, freshwater on the Outer Banks is found within the sandy underlying soils (fig. 98). Rainfall seeping directly into the porous sand creates and sustains these relatively shallow unconfined aquifers. Some of the infiltrated water flows laterally through the sand toward the edges of the island where it discharges into the ocean and sound. The remainder percolates downward through the soil until it eventually contacts sediments that are saturated with salty ocean water. At the interface between the fresh and salty water, a zone of intermixing produces a layer of brackish water. These three distinct zones of water compose the groundwater system of a barrier island.

Lower-density freshwater forms a lens that floats on the saltier layers. The size of the freshwater lens, or near-surface aquifer, naturally varies depending upon precipitation. When rainfall is above normal, the aquifer expands; when it is below normal, the aquifer shrinks. Regular rainfall, then, is essential for recharging the freshwater aquifer and maintaining an adequate groundwater supply.

Precipitation is not the only factor affecting the size of the aquifer, however. Individual homeowners and municipalities on the Outer Banks draw freshwater from the aquifer through groundwater wells. As population increases, so too does the demand for water. When the demand exceeds the amount of water being recharged by precipitation, the aquifer shrinks. Thus, keeping the aquifer stable is a function of both natural supply and public demand.

Demand for drinking water has increased sharply since the early 1980s, when the Outer Banks tourist industry began its rapid growth. In 1970, the permanent population of the Outer Banks was 6,253; by 2000, it was 53,859 (Street and others, 2005). During the summer tourist season, this number grows to nearly one-half million on any given day. This enormous increase in population, particularly during the summer, is depleting Outer Banks aquifers.

By the late 1980s, freshwater demand was beginning to exceed renewal supply in some locations. Dare County's solution was to desalinate brackish groundwater by use of reverse osmosis, and the County installed the first reverse-osmosis desalination plant on the Outer Banks in 1989. Currently, the County operates three reverse osmosis plants, one each in Kill Devil Hills, North Hatteras Island, and South Hatteras Island. Desalination of brackish groundwater is becoming a primary method of producing potable water in the coastal counties of Dare, Currituck, and Hyde. These three counties now have the capacity to desalt nearly 11 million gallons of groundwater daily. Looking into the future, continued population growth on the Outer Banks will further stress freshwater supplies. Inevitably, the fraction of the water supply coming from the withdrawal and treatment of brackish water will also grow.

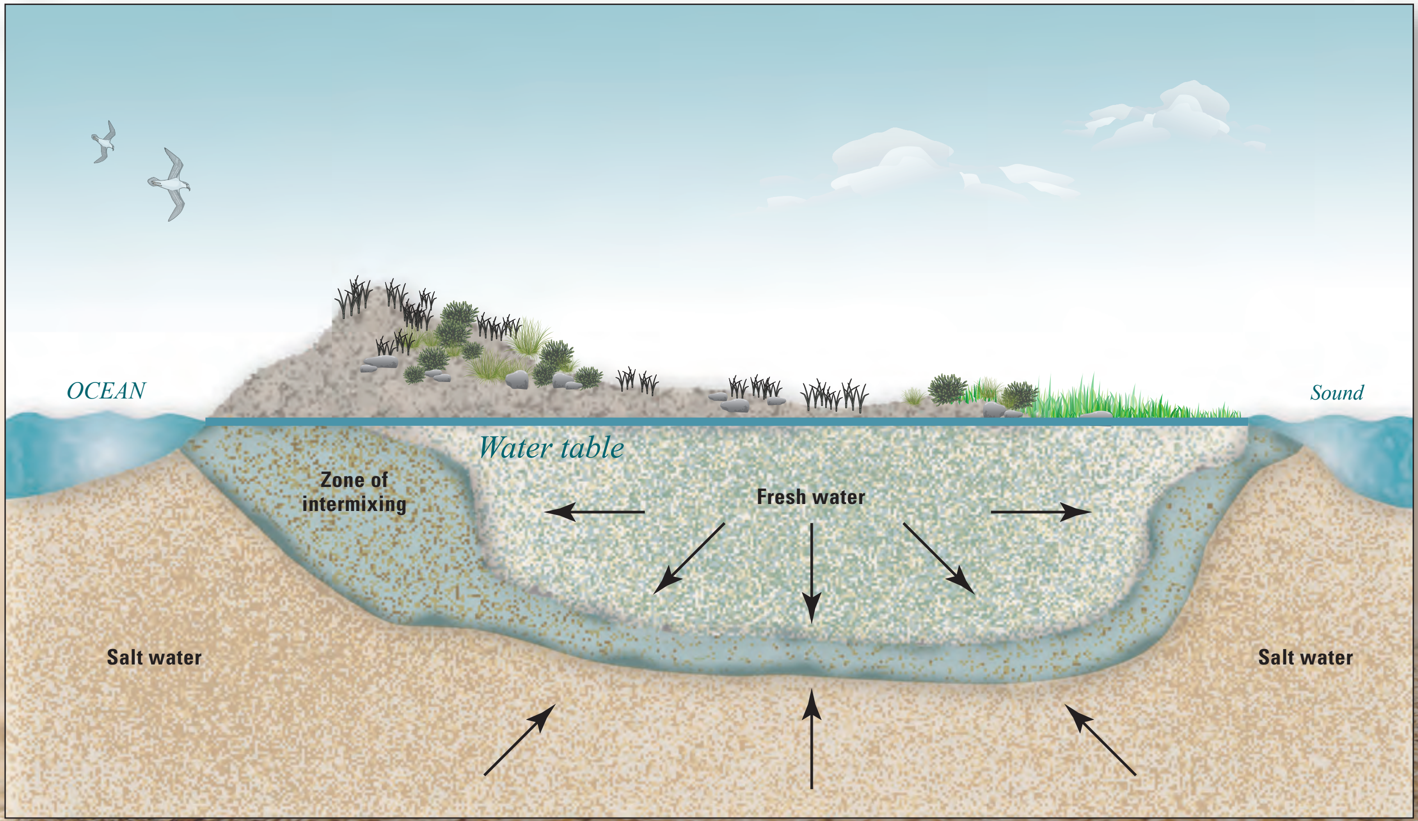

Figure 98. A barrier island aquifer in cross section. Arrows show the path of water movement *(adapted from Cohen and others, 1968). (Symbols courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).*

Opportunities for Future Research

This report presents an overview of the geological history of the Outer Banks of North Carolina: how the islands formed, how they have changed, and why they will continue to change. It includes an assessment of human activities since the time of the first settlements. The purpose is not just to describe the natural processes but to point out how some of these processes produce environmental hazards. Data are presented that allow a holistic look at changes in the barrier island system.

Natural processes are key indicators of areas that are particularly hazardous to develop. Data on erosion and overwash penetration rates, coupled with land use information, can provide a basis for guiding future development away from the more hazardous areas and into locations of greater relative safety. Similarly, such data can be effectively used to evaluate various hazard mitigation techniques and to choose those that offer the most protection with the fewest negative effects.

The natural configuration of barrier island coastlines, as determined by coastal processes, is not straight; it tends to have sinuous curves and bulges. Some homes on the Outer Banks constructed in the 1950s are still standing today, having weathered hundreds of storms, even the destructive 1962 Ash Wednesday northeast storm. Other houses have disappeared. The vulnerability of some places along the coast is not simply a matter of chance but, rather, is part of a pattern. Research suggests that even for individual sites along the barrier islands, natural processes result in shoreline forms that are systematic or recurring (Dolan, Lins, and Stewart, 1980).

If hazard zones along the barrier islands are distributed systematically, they should also be predictable. Although detailed historical information for establishing past patterns is not always available, evidence suggests that if a section of sedimentary coast has experienced storm damage and serious erosion in the past, it is likely to experience more in the future.

Barrier island inhabitants continually assess environmental processes and the associated potential for hazardous conditions brought about by island changes caused by natural and human processes. Although precise predictions of storm timing and location are not possible, general assessments of along-the-coast variations in hazard probabilities are possible. It is possible that one of the most important elements in future hazard research and assessment is a concept that has so far been explored principally on an intuitive level: that storms provide the energy for coastal change and that geomorphological characteristics determine how that energy is distributed.

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Glossary

A

anticyclone A central region of high atmospheric pressure surrounded by large-scale circulation of winds; it is clockwise in the Northern Hemisphere, counterclockwise in the Southern Hemisphere.

B

back barrier bay The relatively calm, shallow, and protected body of water that separates a barrier island from the mainland.

backshore beach The area of a shore that lies between the average high tide mark and dune vegetation; it is affected by waves only during severe storms. It is commonly referred to as the backshore.

barrier dunes Unconsolidated mounds of wind-blown sand on the ocean side of a barrier island, typically covered with sparse to dense vegetation, and that separate the beach from the interior environments of the island.

breakwater A structure sheltering a harbor, anchorage, or stretch of beach that provides protection from waves.

C

cape A land area that projects seaward from a continent or large island and that prominently changes the direction of the shoreline.

coastal plain An extensive area of low relief, bounded by the sea on one side and by a zone of higher relief on the landward side, that typically is underlain by strata that dip gently and uniformly toward the sea.

continental shelf The relatively shallow (no more than 200 meters deep) seabed surrounding a continent and extending from the shoreline to the continental slope, where the seabed abruptly drops to the deep ocean floor.

cyclonic The rapid inward circulation of air around a low-pressure center, flowing counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere, that is usually accompanied by stormy weather.

D

Dolan-Davis Intensity Scale A classification system for characterizing the intensity of coastal extratropical storms (nor'easters or northeast storms), ranging from 1 for a weak storm that does no damage to 5 for an extreme storm that does extensive damage.

deep water wave A surface wave having a length less than twice the depth of the water.

E

erosion setback A prescribed distance from the shoreline to a coastal feature or structure within which all or certain types of development are prohibited because of local rates of erosion.

estuary A partly enclosed coastal body of water with one or more rivers or streams flowing into it and with a free connection to the open sea.

extratropical cyclone A low-pressure system that forms in the midlatitudes (approximately 30° to 60° north and south of the Equator) and that gets its energy primarily from temperature differences in the lower atmosphere. Cold fronts and warm fronts are typically associated with extratropical cyclones. Northeast storms are extratropical cyclones that move northward along the East Coast of the United States.

eye, eyewall The eye is a circular region of mostly calm weather at the center of strong tropical cyclones. It is typically 30–65 kilometers (20–40 miles) in diameter and has the lowest barometric pressure in the hurricane. The eyewall is a ring of towering thunderstorms surrounding the eye that produces the storm's highest wind speeds.

F

fetch The length of water over which a given wind has blown. It is also referred to as fetch length. The longer the fetch and the higher the wind speed, the larger and more powerful the waves will be.

flood tidal delta Sandy shoals on the estuarine side of a tidal inlet that form on a rising (flooding) tide.

foredune A coastal dune or ridge that parallels the shoreline of an ocean or large lake and is stabilized by vegetation.

foreshore beach The area of a shore that lies between the average high tide mark and the average low tide mark. It is also commonly referred to simply as the foreshore.

G

geomorphic A physical characteristic associated with the shape or surface configuration of Earth.

groin A shore protection structure that extends from the backshore into the surf zone, perpendicular to the shoreline. A groin is intended to build up an eroded beach by trapping littoral drift or to retard the erosion of a stretch of beach.

H

Holocene marine transgression The worldwide rise in sea level and inundation of shorelines that began around 12,000 years ago, caused by the melting of Pleistocene ice sheets, ice caps, and mountain glaciers.

I

inshore The zone of variable width extending from the low tide mark through the surf zone, where waves are transformed by interaction with the sea bed.

inshore current The horizontal movement of water inside the surf zone, including longshore and rip currents.

L

littoral drift Sand and coarser material moved in the surf zone by waves and longshore currents.

longshore current The movement of water in the surf zone, generally parallel to the shoreline, generated by waves breaking at an angle to the shoreline.

longshore sediment transport The movement of sedimentary material parallel to the shore.

lunar tides That portion of the daily rising and falling of the ocean and coastal waters that can be attributed directly to the gravitational attraction of the Moon.

M

mean low water The average of all low-water heights observed during a 19-year-long National Tidal Datum Epoch; the previous 19-year period was 1983–2001.

microtidal A tidal range of less than 2 meters (6 feet).

midlatitude The area of the earth between the tropics and the polar regions, approximately 30° to 60° north and south of the Equator.

N

neap tide The tide occurring at the first or last quarter of the moon (quadrature) when the tide-generating forces of the sun and moon oppose each other and produce the smallest difference between high and low tide.

northeast storm A type of extratropical cyclone that occurs along the East Coast of the United States and Atlantic Canada, so named because the storm travels to the northeast from the south with strong onshore winds that blow from the northeast. Also known more commonly as a northeaster or nor'easter.

northeasterly winds Winds that blow from the northeast.

O

overwash The mass of water and sediment that flows over the crest of a beach and that does not directly return to the ocean. In the field of coastal geology, and as used throughout this book, "overwash" refers to a landward flux of sediment due to overtopping of a dune system typically during intense coastal storms.

overwash fan, overwash flat A fan-like landform of sand washed over a barrier island or spit during a storm and deposited on the landward side. Overwash fans can be small to medium sized and completely subaerial, or they can be quite large and include subaqueous margins in adjacent lagoons or estuaries.

P

perigee, perigean The point in the orbit of an object around the earth that is nearest to the center of Earth.

period, long period, short period The interval of time between successive occurrences of the same state in an oscillatory or cyclic process. In the context of waves, long period waves typically have a frequency of minutes to hours, whereas short period waves typically have a frequency of less than 30 seconds.

primary dunes Accumulations of sand derived primarily from the beach and generally closest to the shoreline. They are dynamically linked to beach processes and are strongly influenced by wave action as both a constructional and an erosional force.

S

Saffir-Simpson Hurricane Scale A hurricane intensity categorization system, ranging from 1 to 5, based since 2012 on sustained wind speed. A Category 1 hurricane has sustained winds of 74 to 95 miles per hour and is capable of producing some property damage. A Category 5 hurricane has sustained winds of 157 miles per hour and higher and is likely to produce catastrophic damage.

screw-pile lighthouse A lighthouse standing on piles, the feet of which each have a wide helical blade that is screwed into sandy or muddy sea or river bottoms.

shoal A shallow place in a body of water, such as a sand bar or reef, that constitutes a hazard to navigation.

significant wave height The average height of the highest one-third of waves present during a specified interval of time.

sound A body of water roughly parallel to the coast and separated from the open ocean by barrier islands.

spring tide The tide occurring at the new or full moon when the tide-generating forces of the Sun, Moon, and Earth are aligned with each other (syzygy) and produce the largest difference between high and low tide.

storm surge A rise above normal water level on the open coast, due to wind stress that piles water up onto the coast. The very low atmospheric pressure typical of a hurricane or intense extratropical cyclone also amplifies storm surge.

subtropical cyclone A storm system that has some of the characteristics of both a tropical and an extratropical cyclone.

T

tidal range The difference in height between consecutive high and low water levels.

tropical cyclone A generic term referring to a warm-core storm system that forms in a maritime tropical air mass. It ranges in intensity from a tropical depression (maximum sustained winds less than 39 miles per hour) to a tropical storm (maximum sustained winds of 39 to 74 miles per hour) to a hurricane (maximum sustained winds greater than 74 miles per hour). “Warm core” means that at any height in the atmosphere the center of the cyclone is warmer than its surroundings; this characteristic separates tropical cyclones from other cyclonic systems.

tropical latitude The region of Earth adjacent to the Equator, bounded on the north by the Tropic of Cancer (23.4°N) and on the south by the Tropic of Capricorn (23.4°S).

W

washover fan, washover flat A fan-like landform of sand washed over a barrier island or spit during a storm and deposited on the landward side. Washover fans can be small to medium sized and completely subaerial, or they can be quite large and include subaqueous margins in adjacent lagoons or estuaries. Major or repeated overwash events produce a larger depositional area known as a washover flat.

wave angle The horizontal angle (azimuth), measured with respect to the shoreline, at which a wave strikes the shore.

wave runup The maximum vertical extent of a wave washing up on a beach (swash) above mean sea level.

wavelength, long wavelength The horizontal distance between wave crests (or troughs) on two successive waves as measured perpendicular to the crest (or trough). Waves that typically have long wavelengths include seismic sea waves (tsunamis) and tide waves (produced by the gravitational attraction of the Moon and Sun).

wind shear A difference in wind speed and direction over a relatively short distance in the atmosphere. Wind shear has both vertical and horizontal components. Horizontal wind shear is found across weather fronts and near the coast, and vertical shear is found typically near the ground or sea surface—and less commonly at higher levels in the atmosphere near upper level jets and frontal zones aloft.

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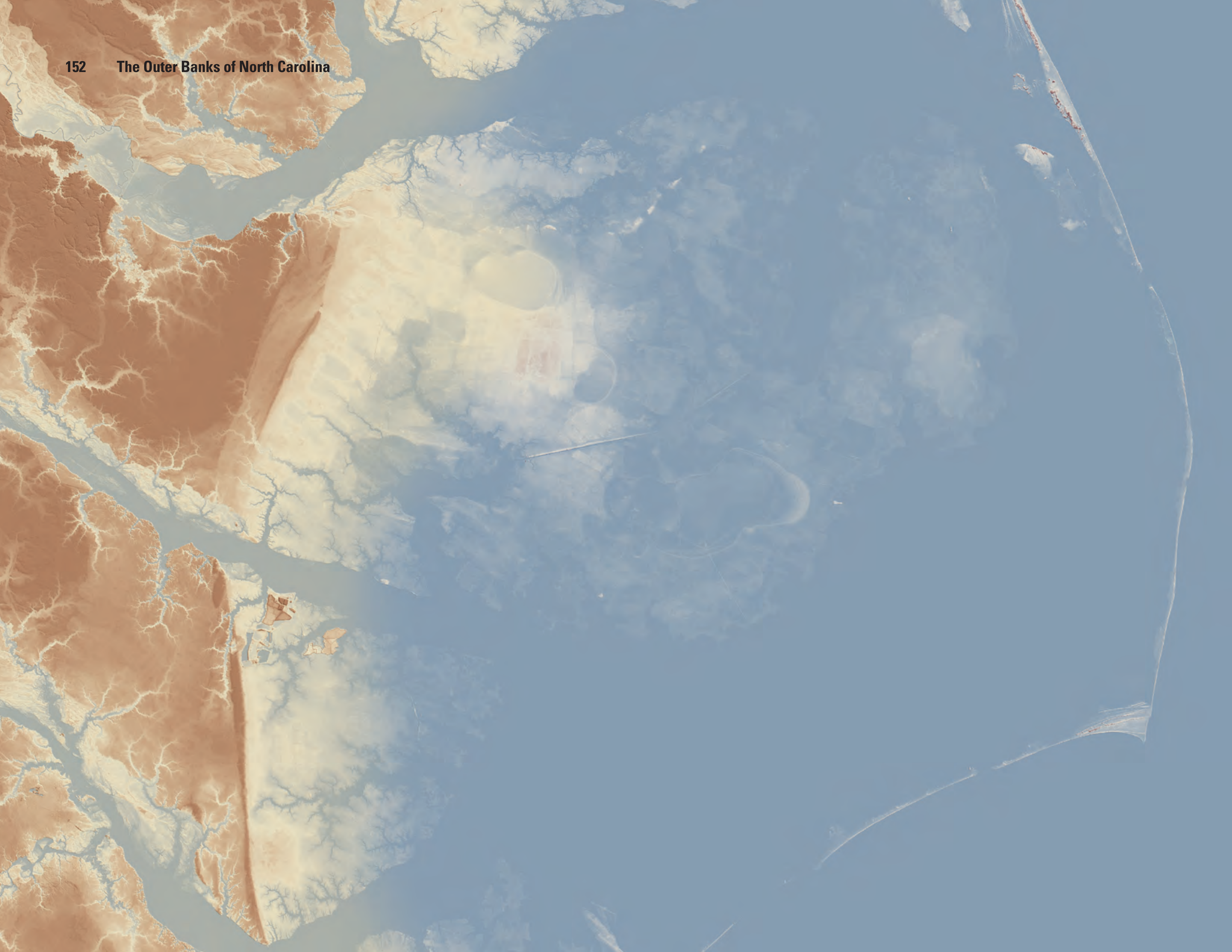

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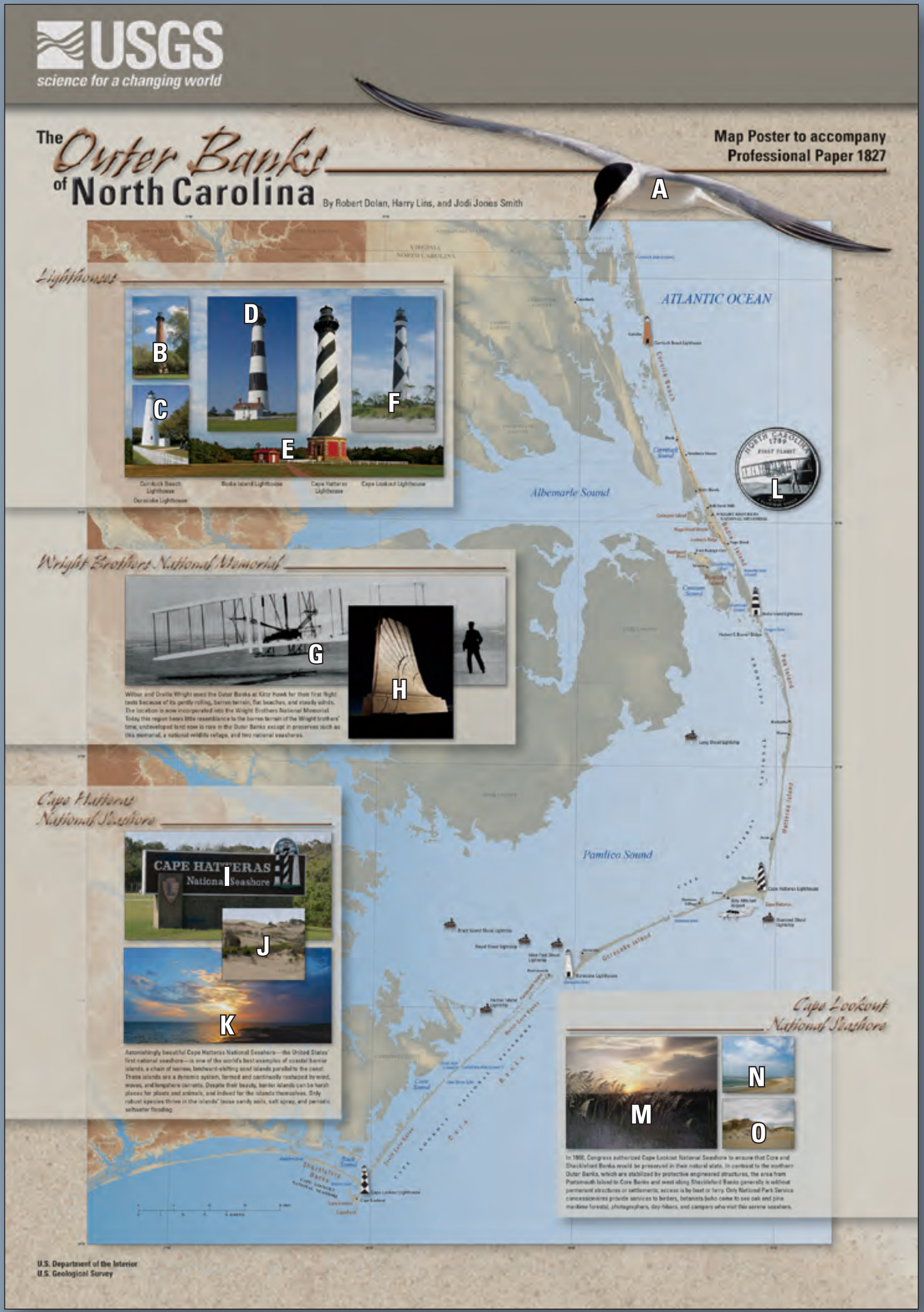

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