Oceanus

Volume 23, Number 4, Winter 1980/81

The Coast

Oceanus®

The International Magazine of Marine Science

Volume 23, Number 4, Winter 1980/81

William H. MacLeish, *Editor*
Paul R. Ryan, *Managing Editor*
Deborah Annan, *Assistant Editor*

Published by Woods Hole Oceanographic Institution

The views expressed in *Oceanus* are those of the authors and do not necessarily reflect those of Woods Hole Oceanographic Institution.

Editorial correspondence: *Oceanus*, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543. Telephone (617) 548-1400.

Subscription correspondence: All subscriptions, single copy orders, and change-of-address information should be addressed to *Oceanus* Subscription Department, 1172 Commonwealth Avenue, Boston, Mass. 02134. Urgent subscription matters should be referred to our editorial office, listed above. Please make checks payable to Woods Hole Oceanographic Institution. Subscription rate: $15 for one year. Subscribers outside the U.S. or Canada please add $2 *per year* handling charge; checks accompanying foreign orders must be payable in U.S. currency and drawn on a U.S. bank. Current copy price, $3.75; forty percent discount on current copy orders of five or more. When sending change of address, please include mailing label. Claims for missing numbers will not be honored later than 3 months after publication; foreign claims, 5 months. For information on back issues, see page 68.

Postmaster: Please send Form 3579 to *Oceanus*, Woods Hole, Massachusetts 02543.

Our Dynamic Coastline

by David G. Aubrey

The coastlines of the world represent one of the most variable and complex regions of our globe. They form the unique interface between the earth's three major constituents: the land masses, the oceans, and the atmosphere. The oceans and atmosphere are constantly changing, a behavior scientists are diligently trying to decipher. In response to this variability, the coastlines change over a spectrum of time scales, trying to achieve an equilibrium with those forces shaping it. The activity of our shorelines is of great human concern because nearly two-thirds of the world's inhabitants live along the ocean margins.

Considering the variability and fragility of the world's coastlines, we clearly need to understand the forces sculpting shorelines and how these fragile boundaries respond. Our knowledge of the complex interactions between the atmosphere, oceans, and land masses is incomplete. Our ability to predict variability in this system is woefully inadequate at times (the most common example of this is the media weatherman, who opens himself to violent criticism with each broadcast). Coastal zone management must rely heavily on scientific knowledge to be effective in protecting and preserving the nation's shorelines, while minimizing the adverse impact on man and his cultural relicts along the coasts. Only by understanding the dynamic nature of the coastal zone can we intelligently manage the limited and fragile resource separating the continents from the oceans.

Most of our nation's coastline includes a thin border of beach sand or other clastic material, backed by either sea cliffs, more water, or low-lying plains. Stretches of shoreline lacking beaches generally have sea cliffs plunging directly to the water's edge. Both beaches and sea cliffs serve to buffer the continents from the oceans' fury. Some regions are highly successful, others fail alarmingly. Beaches on the south shore of the island of Martha's Vineyard, Massachusetts, are receding at the rate of 3 meters per year. The Atlantic-facing shores of Cape Cod, Massachusetts, are backed by sea cliffs eroding at a rate of 1 meter per year. Lighthouses and other structures have been relocated inland to avoid the tenacious reclamation of land by the sea.

The major forces modifying beaches on a brief time scale are winds, waves, tides, storm surges, and man. On geological time scales, the slow sea-level rise along much of the nation's coast causes beaches to migrate landward and to contract. Hurricanes and winter storms provide vivid demonstrations of the frailty and vulnerability of beaches; this, combined with local sea-level rise, dooms many of our beaches to recede, accelerating coastal damage during hurricanes and storms.

Barrier beaches represent a special type of shoreline, bordered on one side by an ocean, sea, or gulf, and on the other by a protected body of water (Figure 1). These beaches may be completely separated from land, in which case they are called barrier islands. Barriers attached on one side to land are called barrier spits. When completely enclosing an embayment with only a single channel to the ocean, they are known as baymouth bars. In this article, these classifications are implied in the general term barrier beach. The distinction among these different structures is often temporary, as storms often remold shorelines into a different form within a few hours.

All beaches, including barrier beaches, are in many ways similar in their response to nature's forces. Storm waves, most frequent in winter months, erode beaches, whereas more quiescent waves return sediment shoreward and rebuild beaches. Waves approaching at an angle move sand along the beach. This longshore transport may have no net effect on the appearance of the beach, or it may accrete or erode the beach, depending on whether equal or unequal amounts of sand enter

Cliffs of clay at Gay Head, Martha's Vineyard, move back about 3 meters per year through wave action and wind erosion. (Photo by Jan Hahn)

Crescentic bars occurring off Nauset Inlet on Cape Cod, Massachusetts, in May, 1953. The bars extend for at least 5 kilometers, with a spacing of hundreds of meters. A complex wave pattern exists in the lee of these crescentic bars. (Courtesy U.S. Coast and Geodetic Survey)

Going to the Beach

This has been the Year of the Coast, an effort principally by environmentalists to focus national attention on the more than 80,000 miles of American fringe lands. It's about time, and it may be way past time.

On a recent assignment for *Smithsonian*, I had occasion to travel a fair section of the coast — starting at Galveston and working east from Mobile around the thumb of Florida and north through the Outer Banks of North Carolina to New York. There are still plenty of wild stretches, miles we have left lonely. But generally where development has occurred, it has been fast and formless. The west coast of Florida has semblances of style — a domino skyline, a sweep of bay bridge — but the net effect is surfeit. The Outer Banks are protected as a national seashore, but where protection stops, a kind of fancy, second-home shantytown begins. Prices are phenomenal, particularly on barrier islands; a thousand dollars a shoreline foot is often asked and gotten, sometimes two thousand. "People are going to live on the coast," the mayor of an Alabama beach resort told me. "And they're not making any more coast."

The national centrifuge has spun three of four Americans out to within a hundred miles of some coast, oceanic or lacustrine. By the end of the decade, three out of four will be living within 50 miles of the sea, some predictors say. If they are right, the pressures on some of our most beautiful, delicate, and productive areas will be placed under severe stress. The trends are there: we have drained, filled, or otherwise lost about 40 percent of our wetlands, and the process continues at the rate of some 300,000 acres a year; that shrinkage, plus pollution of nursery bays and estuaries, has caused sharp drops in local shell and finfish harvests.

The risk is not entirely to the environment. Sea level is rising, a fact the buying public does not seem to have grasped. Precise measurements are difficult, but most scientists will settle for a mean value of about one foot a century worldwide. As the sea rises, coasts submerge — except in areas of glacial rebound — and coastlines retreat inland. We can armor choice shorelines with sea walls and groins, but even these brutally expensive structures can't give property owners more than a few decades of protection.

Curiously, the beach boom has been going on during a lull in hurricanes. More than a hundred of them have come ashore since the start of the century, but the incidence is down now. The result is that around eight out of ten Americans living on the coast have had no experience with really heavy weather; many of them tell poll takers they don't pay much mind to killer storms. That insouciance simply is not healthy. Few people know, or seem to care, that the worst natural disaster by far in this country occurred when a hurricane slammed into the barrier island of Galveston, Texas, in 1900, killing 6,000 in the city and another 2,000 or so nearby. Today, experts say, if a big storm like Camille, rated five on a scale of five, were to come ashore in a heavily urbanized area like, say, Miami, the results would dwarf Galveston.

Scientists and government officials are paying much more attention today to coastal processes and their interaction with social stresses of coastal crowding. Nearshore oceanography tends to be difficult work: tides and topography can make a washing machine out of the inshore ocean. But as the articles in this issue indicate, we are learning. We are beginning to understand how the sea shapes beaches, how to predict where storms may open inlets, how to spot high-hazard areas. We are beginning to understand the effects on the coastal biota of at least some pollutants, including oil and some heavy metals. We can, upon occasion, identify and correct the causes of dangerous siltation or variation in the salinity of lagoons and estuaries.

Equally important, we are facing up to the impact of governmental policies on shoreline development. Much of the infrastructure of that development is underwritten to a degree by federal programs. Those would include roads and bridges, sewage treatment facilities, flood control, and hurricane protection. Coastal communities meeting flood-related building standards are eligible for federal insurance at bargain premiums. Revision of these programs may not halt our rush to the salt, but it could make it more likely that the costs of living in harm's way will be more equitably apportioned.

William H. MacLeish

Figure 1. Barrier beach systems are composed of a thin vegetated beach separating a major body of water from a protected bay and adjacent land mass.

and leave a particular coastal stretch. Beaches may be long or short, straight or sinuous, depending on the forces modifying them and the available sediment. Two major processes are unique to barrier beaches: tidal inlet changes (both their formation and migration), and overwash processes. During storm conditions, these processes can control the poststorm barrier beach configuration, far outweighing other agents that are modifying the beach at that time.

Geological Factors

The shape and characteristics assumed by a stretch of coastline reflect a myriad of geological forces and present-day processes. A major geological factor controlling shoreline features appears to be plate tectonics (see *Oceanus,* Vol. 17, No. 3), which influences the width and bathymetric detail of the continental shelf as well as the local rise or fall of sea level. The rate of denudation of inland regions coupled with the supply of sediment to the coastline are other factors. The local conditions of some shorelines mirror river drainage patterns, faulting, and slumping, as well as biological processes (such as on coral beaches or mangrove beaches). Wind patterns, climate, and tidal range all contribute to the complex nature of shorelines.

Sea-level changes, both eustatic (worldwide) and local, play an important role in long-term beach development. A eustatic sea-level change results from glacial activity; as glaciers melt, worldwide sea level tends to rise, while as glaciers enlarge, worldwide sea level tends to fall. Since the world is currently in an interglacial period, sea level is relatively high. A schematic sea-level curve for the eastern United States (Figure 2) shows a sea-level stillstand near 15,000 years before present (BP), followed by a relatively rapid rise up to 5,000 years BP, when sea level was approximately 5 meters below the present level. Sea-level rise since then has averaged approximately one millimeter per year, gradually encroaching on the continents.

Superimposed on the eustatic sea-level curve are other sea-level fluctuations that result in nonuniform rates of relative sea-level rise around the world. The primary forces causing noneustatic relative sea-level changes are tectonism (such as along the Pacific coast), glacial rebound resulting from land masses gradually readjusting to removal of glacial loading (such as in Scandinavia), and seasonal changes in sea level that are the result of freshwater inflow and heating and cooling cycles in the ocean (steric effects). Tide gauge records from the United States over the last 40 years show the entire mainland coast submergent relative to the oceans, with rates ranging from 3 millimeters per year in New England to about 15 millimeters per year

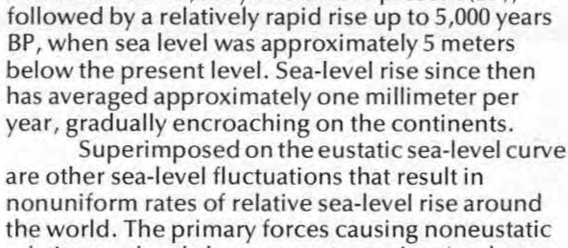


Figure 2. A sea-level curve for the last 35,000 years clearly shows the rise and fall of sea level associated with worldwide glaciation. (After Milliman and Emery, Science *1968)*

along the Gulf coast. Clearly both eustatic and local effects are important factors in determining relative rates of sea-level rise, and the ultimate fate of beaches.

Nearshore Hydrodynamics

Besides the geological factors, water motions impinging on beaches in large part control the behavior of the shoreline. The major events modifying beaches are hurricanes and winter storms. Hurricanes often have dramatic effects on coastal regions, bringing with them large waves, storm surges, and devastating winds. Hurricane Frederic in September, 1979, caused approximately $1 billion in damages along the Gulf coast (see page 47). The last major hurricane to devastate the Atlantic coast was Donna in 1960. Many coastal and atmospheric scientists believe a major hurricane will strike a populated U.S. coastal region in the next few years, and will surely cause widespread damage.

Winter storms also are responsible for extensive coastal destruction, often affecting much greater stretches of coastline than a single hurricane. Large waves, winds, and storm surges are also associated with these winter storms. The Ash Wednesday storm of March 7, 1962, caused millions of dollars of damage along the eastern seaboard. Each year, nearly a hundred such storms along the U.S. coast shape and modify the beaches.

The mean circulation in the nearshore zone can be schematically represented by a generalized circulation cell (Figure 3). Waves approach the shore at an angle, driving a longshore current in the direction of wave propagation, interrupted periodically by seaward-flowing rip currents. This simple model illustrates the major components of nearshore circulation, but obscures the complexity of the mutual interactions of these various flow fields. To understand how a beach responds to a hurricane, storm, or calm-weather wave field, we

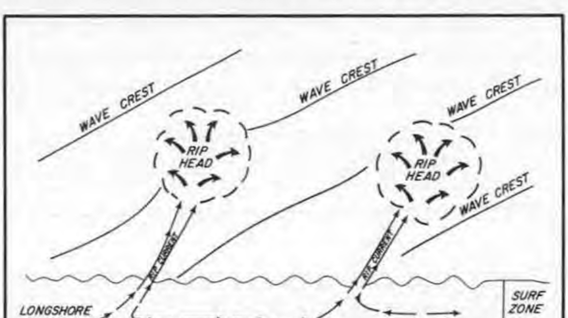


Figure 3. Nearshore circulation cell consisting of incident waves, wave-driven longshore currents, and seaward-flowing rip currents.

first need to know how waves behave as they approach the shoreline.

Surface gravity waves, which are the waves we observe on the sea surface, are fueled by winds blowing over the oceans. As waves propagate across the open ocean, they lose some energy, but can remain coherent over distances of thousands of miles. Once the waves reach shallow water,* however, they begin to transform and lose energy more rapidly. The loss of wave energy in shallow water is primarily through bottom friction; as waves pass over the bottom, energy is dissipated in the bottom boundary layer. Some of the dissipated energy results from moving sediment, the rest goes into the production of turbulence which eventually is dissipated as heat.

The bottom boundary layer is the transition region near the seabed where the wave and current motions decay to zero. The detailed structure and dynamics of this boundary layer are as important as they are complex; to understand the mechanics of near-bottom sediment transport (both bedload, which is material transported along the bed, and suspended load, which is material transported off the bed), we must improve our modeling of the boundary layer.

The changes that waves undergo as they move shoreward or shoal are complex and not entirely understood. The simplest transformation predicts no changes in wave symmetry or period, only changes in height and wavelength. Except for dissipation, a shoaling wave conserves its rate of flow of energy (energy flux) from deep water up to the breaker point. As it shoals, the wavelength constantly decreases; since the period remains the same, the wave speed (wavelength divided by period) also decreases. The wave height initially decreases as shoaling occurs, then increases shoreward. This linear shoaling model predicts symmetrical wave forms and symmetrical near-bottom wave motions.

Waves can change direction as they move shoreward; this phenomenon, called wave refraction, is analogous to optical refraction. As waves propagate into shallower water, their direction changes such that wave crests become more parallel to shore; in very shallow water waves break nearly parallel to the shoreline. Other wave shoaling effects are diffraction and reflection, where the seafloor changes the wave properties because of sudden bottom irregularities, steep bottom slopes, or longshore bathymetric discontinuities.

Field observations show that the linear shoaling model does not adequately represent

*Shallow water here is roughly defined as water depth less than half the deep-water wavelength, approximately 175 meters for a 15-second wave or 38 meters for a 7-second wave.

Field and laboratory observations are consistent with theories about nearshore edge waves, suggesting their importance in nearshore sand movement. These longshore periodic waves may influence rip current formation and even the beach configuration itself.

Storm systems affect beaches other than just through waves. Storm surges can raise the mean water level near the coast, enabling destructive waves to erode the beach at higher and higher levels. Storm surge is composed of several components. The first is an "inverse barometer" effect, where sea level rises in response to lowered atmospheric pressure associated with storms. A drop in atmospheric pressure of 2 millimeters of mercury is equivalent to a sea-level rise of 3 centimeters. Combined with this barometric effect, a wind blowing onshore during a storm can raise sea level by several meters. The combined storm surge can significantly contribute to storm damage along coasts, and the development of overwashes and inlets along barrier beaches. Other water motions also may influence beach processes, but generally to a lesser degree. Internal waves, shelf circulation patterns, Gulf Stream eddies, and other low-frequency motions may influence any particular beach in an intricate fashion.

Beach Response

Our understanding of how beaches respond to waves and tides is largely empirical, although significant theoretical advances have increased our knowledge of the physics of sediment transport. The U.S. National Oceanic and Atmospheric Administration's Sea Grant program recently has been sponsoring a major effort to better understand how beaches work; this program is called the Nearshore Sediment Transport Study (NSTS). Approximately 10 scientists serve as principal investigators on this project, designed to "perfect relations for the prediction of sediment transport by waves and currents in the nearshore environment." The study emphasizes field measurement of nearshore wave and current behavior at three different sites, as well as theoretical and empirical modeling of surf zone hydrodynamics and sediment transport. This study is contributing to our understanding of the behavior of different beaches as they are exposed to various driving forces.

Although beaches change in a complex manner, some aspects of their behavior can be correlated with particular aspects of the forcing conditions. The most obvious example is the gradual encroachment of the sea onto beaches, responding in part to local sea-level rise. As sea level rises, beaches retreat landward, often leaving peat deposits, tree stumps, and other coastal forest remnants exposed on the open-ocean beaches. Accompanying this shoreward migration may be a narrowing of the beaches and consequently a reduction in their capacity to act as buffers to ocean storms and waves. This beach retreat and narrowing is not a result of sea-level rise alone; it also reflects fluctuations in the availability of sediment in the nearshore zone as well as variations in storm and wave climates.

The movement of sediment along a beach is conveniently divided into on/offshore sand transport and longshore sand transport. Although this division is arbitrary and ignores the very real mutual interactions between these modes, on/offshore and longshore transport do respond generally to different features of the incident wave field. Both modes of transport can be responsible for patterns of beach erosion or accretion at a particular location; it is important to distinguish which mechanism is responsible for coastal change whenever shoreline stabilization methods are considered.

On/offshore transport results from shoaling asymmetrical waves, moving sediment both landward and seaward, alternately acting with and against the influence of gravity. Wind- and wave-induced currents within the surf zone may modify this transport pattern. Field and laboratory experiments suggest that long, low waves build up a beach to a "berm profile," whereas steep, short waves erode the beach face, causing a "bar profile." Since coastal wave climates have a seasonal variability, beach changes also have a seasonal character to them. To better understand the mechanics of on/offshore sediment movement, we need to better understand nonlinear wave shoaling, nonlinear surf zone energy transfers, wave breaking phenomena, wave boundary layer structure, and the bedload/suspended sediment transport transfer functions.

As waves approach and break along a shoreline at an angle, driving a longshore current within the surf zone, sediment moves alongshore in the direction of wave advance. Surf zone structures and tidal inlets interrupt this littoral drift, causing modifications of downdrift beaches. If more sediment enters a coastal area than leaves through longshore transport, the beach accretes. If more longshore drift leaves an area than enters, erosion results. There are many notable examples of longshore sand starvation caused by structures, and the subsequent beach erosion (Figure 5).

Tidal inlets interrupt littoral drift, forcing sand to bypass either by moving in and out of the inlet, or along an offshore delta. When new inlets are formed during storms, sand is taken from the nearshore sand budget to build flood and ebb tide deltas. Once these features are well developed, bypassing of sediment to the downdrift barrier beach can occur by natural processes. If the inlet is modified by jetties, bypassing may be more difficult and often must be accomplished by further human intervention.

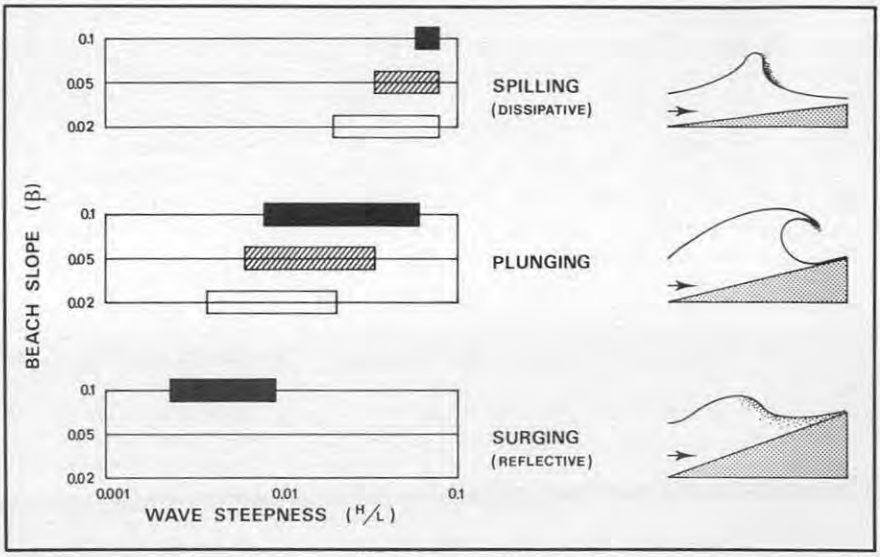


Figure 4. The three primary types of breaking waves are classified according to beach slope and wave steepness (wave height divided by wavelength, H/L). The breaker type influences the nature of water and sand motions near the surf zone.

shallow-water wave behavior. As waves progress shoreward, they steepen and become asymmetrical, with steep, high crests and broad, low troughs. Wave orbital motions become asymmetrical as well, imparting unequal movement to sediment in the onshore and offshore directions, resulting in a net movement of sediment or a finite beach slope. The description of nonlinear wave shoaling, with increased wave asymmetry and transfer of energy between waves of different periods, is of supreme importance in nearshore sediment transport; studies are under way to model and observe this process more thoroughly.

The shoreward propagation of waves is accompanied by variations in the momentum of water waves as well as changes in energy. The resulting force, termed the radiation stress, has widespread ramifications for nearshore processes. Wave set-up and set-down are two results of this radiation stress. As waves shoal, there is an initial slow decrease in wave height, followed by more rapid increase in wave height up to the breakpoint (if dissipation is low enough).

Accompanying the increase in wave height is a tilting of the mean water level down toward the shoreline; this is wave set-down. If the waves were absent, this effect would not occur. Landward of the breaker zone, the wave height decays toward shore; this decay is accompanied by an increase in the mean water level in the swash zone known as wave set-up. Again, this effect is the result of the presence of waves. Wave set-down does not have profound ramifications in beach stability; wave set-up is important, however, as it contributes to the maximum water levels reached during storms and can increase erosion. Radiation stresses also are responsible for generating longshore currents; these are strong currents (up to 2 meters per second) moving parallel to the coast in the direction of wave advance, confined in most part between the breaker point and the shore.

The most dramatic phase of wave shoaling is wave breaking, when the wave becomes so steep and asymmetrical it is unstable. The breaker type is dependent on beach slope and wave steepness (wave height divided by wave length — see Figure 4). Spilling breakers occur with shallow beaches and steep waves, surging breakers occur with steep beaches and waves of low steepness, while plunging breakers result from steep beaches and waves of intermediate steepness. The steepness of the beach has a direct influence on nearshore hydrodynamics, and consequently on beach sand movement. This influence has two major expressions: it affects the transfer of energy from wave motions to long-period motions in the surf zone; and it correlates with run-up patterns in the surf zone.

Field observations have shown that energy is transferred from incident wave periods to long-period motions within the surf zone. This transfer shows up in surf zone measurements of both run-up of waves on beaches and of swash velocities. This transfer of energy could have several causes; one might be the excitation of long-period waves by incoming swell. Theoretical work has demonstrated the possibility of taking energy from incoming surface waves and pumping it into longer-period fluctuations called "edge waves." These edge waves have a longshore periodicity and amplitudes decaying exponentially offshore, whose energy is trapped against the shoreline by refraction. Energy is supplied by incoming ocean waves, and is lost through bottom friction or other dissipation.

Figure 7. Overwash event and inlet formation occurred in February, 1978, on Monomoy Island, Massachusetts, separating a barrier island into two distinct islands. Strong tidal flows between the Atlantic Ocean and Nantucket Sound keep the inlet open.

Figure 8. Multiple parallel offshore bars located off Truro, Cape Cod, Massachusetts, along Cape Cod Bay, where the tidal range is approximately three meters. The bars intersect the shoreline to the north where they become sinuous; bar spacing increases with distance offshore.

Figure 9. Multiple oblique nearshore bars are superimposed on numerous, smaller-wavelength parallel bars off Wellfleet, Cape Cod, Massachusetts, where the tidal range in Cape Cod Bay is approximately 3 meters. The spacing between oblique bars is several hundred meters.

Figure 10. Multiple bars exposed at low tide off El Golfo, Sonora, Mexico, in the Gulf of California, where the tidal range is approximately ten meters. The bars form a confused pattern with both oblique and parallel bars separated by short distances.

formation of a submerged bar under a breaking wave (a breakpoint bar), which moves shoreward under favorable conditions, eventually to weld onto the shoreline as an accretionary feature. As one bar is migrating shoreward, a second breakpoint bar may form, which in turn migrates shoreward. This sequence occurs in both tidal and tideless seas, although it is more common in the latter.

Multiple oblique bars also exist along coastal regions (Figure 9). Their existence is often ascribed to shallow longshore tidal currents; they can exist superimposed on multiple parallel bars that may be wave related. Sometimes oblique bars and parallel bars of the same scale cover the same coastline (Figure 10); although wave forcing is believed responsible for this feature, tidal flows are often contributory (the tidal range in Figure 10 is approximately 10 meters). Crescentic bars often form offshore, with distinct cusps and horns. Their occurrence has been linked by A. J. Bowen and D. L. Inman (1971) to standing edge waves trapped between two longshore features (such as headlands). The region (see introductory photo) has no apparent trapping mechanisms, so other forcing may control the spacing and occurrence of these crescentic bars.

Other longshore periodic features of similar spatial scales include shore-attached hooked bars, with hooks pointing in the direction of longshore transport (Figure 11). The hooked ends of the bars

Figure 5. Santa Barbara, California, presents a notable example of longshore sand entrapment by a coastal structure and resultant severe erosion of downdrift beaches.

Storms can damage coasts severely over very short time intervals. Because of the larger wave energies present during storms, much more sand is moved than during quiescent conditions, both alongshore and on/offshore. The effects of rapid storm erosion were measured at Santa Barbara, California, in February, 1980, by the author and R. J. Seymour of Scripps Institution of Oceanography, as part of the NSTS (Figure 6). Vertical beach changes of up to 2.5 meters occurred over a period of several days. In contrast, the recovery of the subaerial beach to its prestorm configuration will take months or years, emphasizing the mismatch of time scales for erosion and accretion of beaches.

Storms acting on barrier beaches often modify them by two additional processes: overwash and inlet formation (Figure 7). Overwash occurs when the combined effects of erosion, wave set-up and run-up, and storm surge, cause the water to overtop the barrier beach, channeling sand and water into the bay. The overwash process has several major effects. It helps to push sand shoreward, causing the barrier to migrate toward shore. It also destroys the protective dune structure and vegetation, thereby temporarily weakening the barrier and making it more susceptible to future overwash events. Finally, it partly fills the bay (hence reducing the volume of water exchanged by the bay and ocean through tides), and can kill existing vegetation and shellfish.

Tidal inlets, or breakthroughs, can be formed on barrier beaches during storms, often as a result of overwash events. These new inlets can change the flushing characteristics of bays, as well as interrupt longshore sand transport, robbing the nearshore of valuable protection. Inlets may remain open for long periods of time, either coexisting with or replacing former inlets. In many cases, storm inlets close after a short period, leaving tidal flushing to the prestorm inlets. These two processes are instrumental to the shoreward migration and evolution of barrier beach systems; their long-term benefits partly offset the immediate removal of sand from the local sand budget.

In addition to the general on/offshore and longshore transport of sand, nearshore water motions also result in the creation of periodic beach forms; this periodicity may be in either the longshore direction (oblique forms) or shore normal direction (parallel forms). These periodic bed structures most likely result from a periodicity in the driving forces; researchers have been only partly successful in isolating the mechanisms generating these features. One common type of periodic form is the multiple parallel offshore bar (Figure 8): these forms have wavelengths of tens or hundreds of meters and heights of approximately one meter. As with most nearshore features, multiple parallel bars can be formed in a number of ways. One documented sequence consists of the

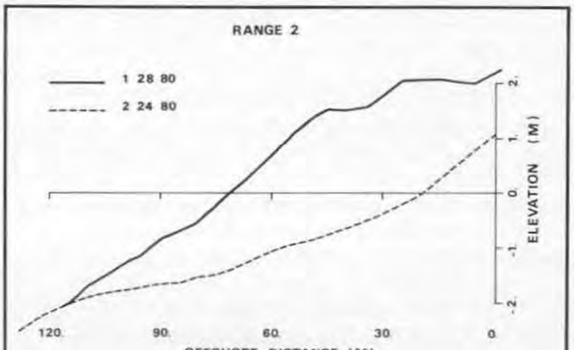


Figure 6. Beach erosion resulting from a series of storms battering Santa Barbara, California, in February, 1980, causing vertical cuts in the beach of up to 2.5 meters, and horizontal beach retreat of up to 60 meters.

are in the zone of most active longshore transport, averaged over a tidal cycle. These features originally may have been bars separating longshore periodic rip currents. If the shore-attached hooked bars result from periodic rip currents, then the origin of periodic rip currents needs to be explained.

Edge waves are frequently blamed for many of these longshore periodic bedforms. Indeed, R. Dolan, B. Hayden, and C. Jones (1979) have even postulated large-scale edge waves as sculpting the numerous false capes along the eastern seaboard. R. T. Guza and Inman (1975), among others, have suggested subharmonic edge waves as a generating mechanism for beach cusps, with some field evidence to support this association. Edge waves are convenient because they have a longshore periodicity and have an infinite number of modes (hence wavelengths). It is straightforward to match the spacing of any longshore periodic feature to some edge-wave mode. Carefully planned, well-instrumented experiments are needed to assess the role of edge waves and other long waves in nearshore hydrodynamics. Other alternative mechanisms, such as surf zone instabilities, need to be explored in greater detail as well.

A Look to the Future

The beaches of the United States, which include the most extensive barrier beaches in the world, constitute a valuable and delicate resource that must be managed intelligently to avoid loss of their recreational benefits, storm protection, and aesthetic appeal. Beaches are complex systems: they are forced by complex atmospheric and oceanic behavior and respond in an equally complex manner.

Our scientific understanding of beaches in some respects is not sufficient to meet the requirements of coastal zone management in establishing beach policies and guidelines. Active research in beach processes in general, including barrier beach systems, must continue in order to fill this need. In addition to continued research, the scientific community must work closely with the public, educating them and communicating the various scientific alternatives available for managing our nation's beaches. The public in turn must become concerned and better informed if we wish to most effectively and least destructively utilize our valuable beaches.

David G. Aubrey is an Assistant Scientist in the Department of Geology and Geophysics, Woods Hole Oceanographic Institution.

All photos taken by the author, unless otherwise noted.

Figure 11. Multiple, shore-attached hooked bars stretching from Provincetown, to points further south along the Atlantic shore of Cape Cod, Massachusetts. The hooks point in the direction of longshore transport, and occur with a spacing of hundreds of meters.

References

Bowen, A. J., and D. L. Inman. 1971. Edge waves and crescentic bars. *Journal of Geophysical Research* 76: 8662-71.

Dolan, R., B. Hayden, and C. Jones. 1979. Barrier island configuration. *Science* 204: 401-402.

Dolan, R., B. Hayden, and H. Lins. 1980. Barrier islands. *American Scientist* 68: 16-25.

Guza, R. T., and A. J. Bowen. 1975. The resonant instabilities of long waves incident on a beach. *Journal of Geophysical Research* 80: 4529-34.

Guza, R. T., and R. E. Davis. 1974. Excitation of edge waves by waves incident on a beach. *Journal of Geophysical Research* 79: 1285-91.

Guza, R. T., and D. L. Inman. 1975. Edge waves and beach cusps. *Journal of Geophysical Research* 80: 2997–3012.

Inman, D. L., and C. E. Nordstrom. 1971. On the tectonic and morphologic classification of coasts. *Journal of Geology* 79: 1-21.

Wright, L. D., J. Chappell, B. G. Thom, M. P. Bradshaw, and P. Cowell. 1979. Morphodynamics of reflective and dissipative beach and inshore systems: Southeastern Australia. *Marine Geology* 32: 105-140.

The Apalachicola Experiment:

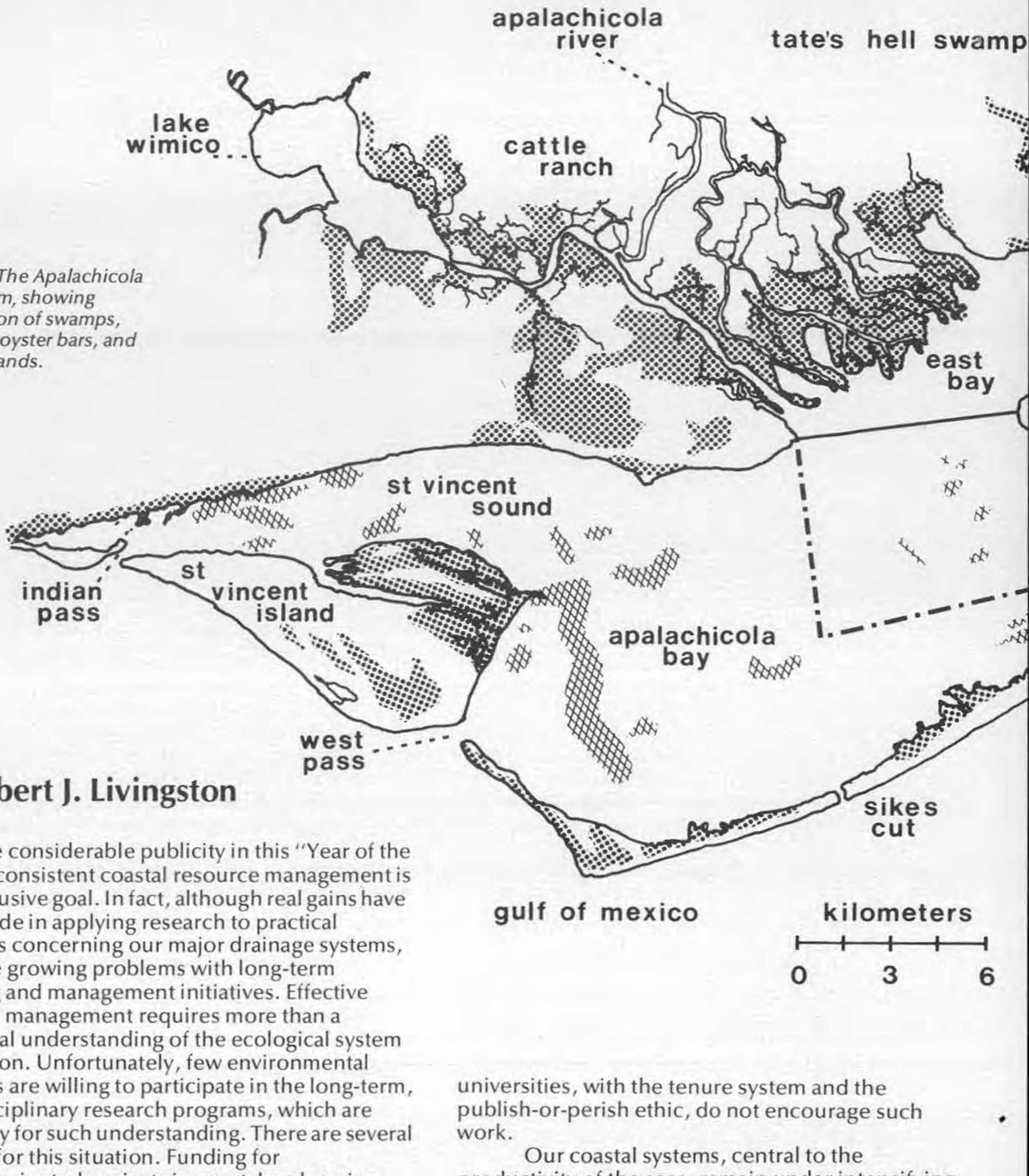


Figure 1. The Apalachicola Bay system, showing distribution of swamps, marshes, oyster bars, and barrier islands.

by Robert J. Livingston

Despite considerable publicity in this "Year of the Coast," consistent coastal resource management is still an elusive goal. In fact, although real gains have been made in applying research to practical decisions concerning our major drainage systems, there are growing problems with long-term planning and management initiatives. Effective resource management requires more than a superficial understanding of the ecological system in question. Unfortunately, few environmental scientists are willing to participate in the long-term, multidisciplinary research programs, which are necessary for such understanding. There are several reasons for this situation. Funding for systems-oriented projects in coastal and marine areas is almost nonexistent. The handful of federal agencies that have the funds and the mandate to carry out such research have often discouraged long-term investigation. There are usually few publications during the early years of a project, and universities, with the tenure system and the publish-or-perish ethic, do not encourage such work.

Our coastal systems, central to the productivity of the seas, remain under intensifying pressure from development and pollution. Millions of acres of productive coastal shellfish beds have been condemned or destroyed because of pollution. Public education and general knowledge of the environment are still lacking. In short,

A Valuable Addition to any Marine Science Library

Oceans and Climate, Vol. 21:4, Fall 1978—This issue examines how the oceans interact with the atmosphere to affect our climate. Articles deal with the numerous problems involved in climate research, the El Niño phenomenon, past ice ages, how the ocean heat balance is determined, and the roles of carbon dioxide, ocean temperatures, and sea ice.

General Issue, Vol. 21:3, Summer 1978—The lead article looks at the future of deep-ocean drilling, which is at a critical juncture in its development. Another piece—heavily illustrated with sharp, clear micrographs—describes the role of the scanning electron microscope in marine science. Rounding out the issue are articles on helium isotopes, seagrasses, red tide and paralytic shellfish poisoning, and the green sea turtle of the Cayman Islands.

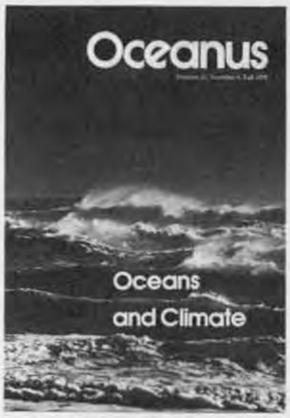
Marine Mammals, Vol. 21:2, Spring 1978—Attitudes toward marine mammals are changing worldwide. This phenomenon is appraised in the issue along with articles on the bowhead whale, the sea otter's interaction with man, behavioral aspects of the tuna/porpoise problem, strandings, a radio tag for big whales, and strategies for protecting habitats.

The Deep Sea, Vol. 21:1, Winter 1978—Over the last decade, scientists have become increasingly interested in the deep waters and sediments of the abyss. Articles in this issue discuss manganese nodules, the rain of particles from surface waters, sediment transport, population dynamics, mixing of sediments by organisms, deep-sea microbiology—and the possible threat to freedom of this kind of research posed by international negotiations.

General Issue, Vol. 20:3, Summer 1977—The controversial 200-mile limit constitutes a mini-theme in this issue, including its effect on U.S. fisheries, management plans within regional councils, and the complex boundary disputes between the U.S. and Canada. Other articles deal with the electric and magnetic sense of sharks, the effects of tritium on ocean dynamics, nitrogen fixation in salt marshes, and the discovery during a recent Galápagos Rift expedition of marine animal colonies existing on what was thought to be a barren ocean floor.

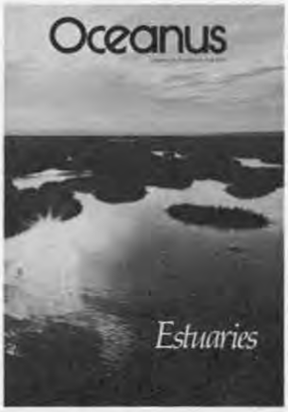
Sound In The Sea, Vol. 20:2, Spring 1977—Beginning with a chronicle of man's use of ocean acoustics, this issue covers the use of acoustics in navigation, probing the ocean, penetrating the bottom, studying the behavior of whales, and in marine fisheries. In addition, there is an article on the military uses of acoustics in the era of nuclear submarines.

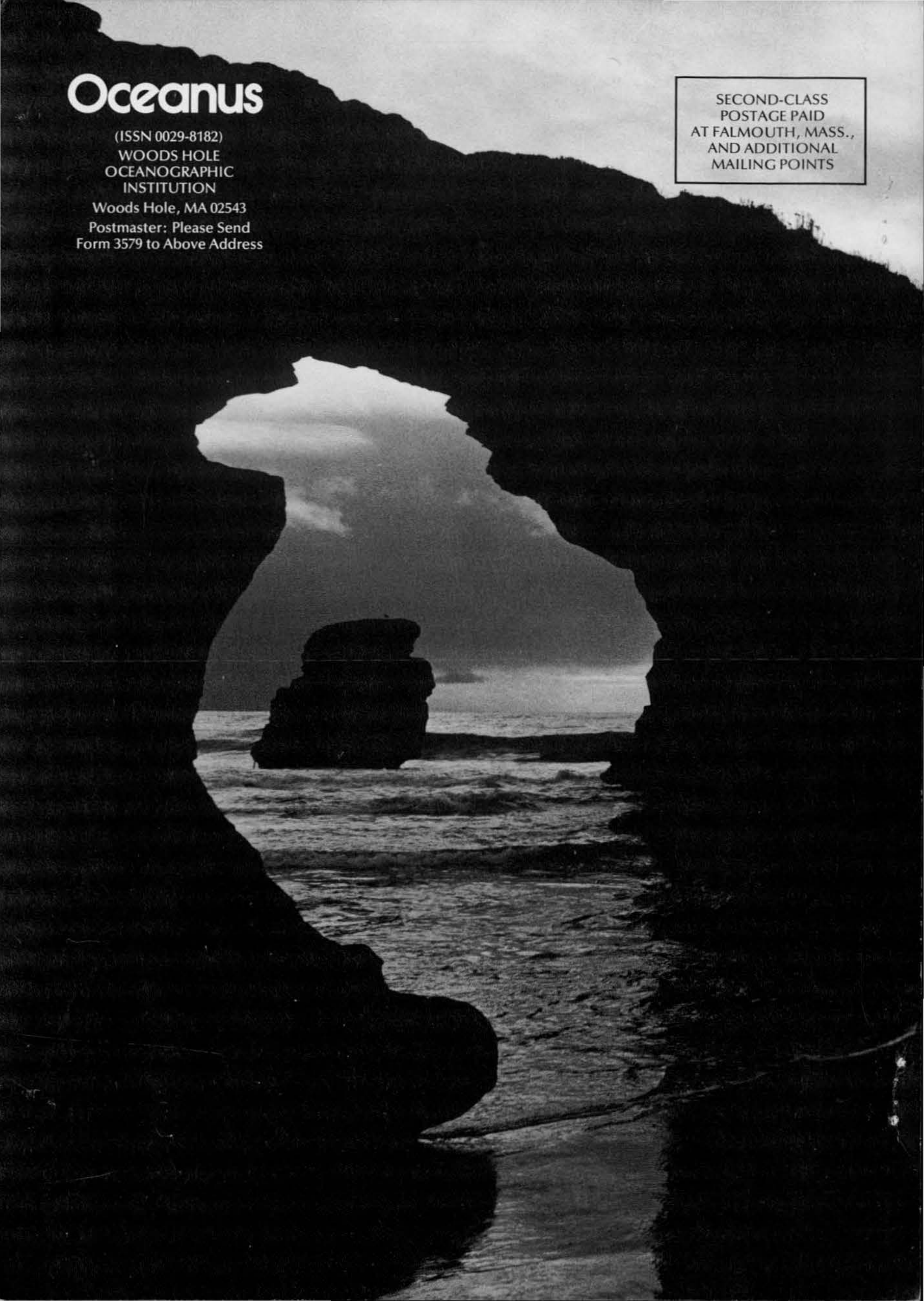
Estuaries, Vol. 19:5, Fall 1976—Of great societal importance, estuaries are complex environments increasingly subject to stress. The issue deals with their hydrodynamics, nutrient flows, and pollution patterns, as well as plant and animal life—and the constitutional issues posed by estuarine management.



ISSUES OUT OF PRINT: Sea-Floor Spreading, Vol. 17:3, Winter 1974 **Air-Sea Interaction,** Vol. 17:4, Spring 1974 **Energy And The Sea,** Vol. 17:5, Summer 1974 **Marine Pollution,** Vol. 18:1, Fall 1974 **Food From The Sea,** Vol. 18:2, Winter 1975 **Deep-Sea Photography,** Vol. 18:3, Spring 1975 **The Southern Ocean,** Vol. 18:4, Summer 1975 **Seaward Expansion,** Vol. 19:1, Fall 1975 **Marine Biomedicine,** Vol. 19:2, Winter 1976 **Ocean Eddies,** Vol. 19:3, Spring 1976 **General Issue,** Vol. 19:4, Summer 1976 **High-Level Nuclear Wastes In The Seabed?** Vol. 20:1, Winter 1977 **Oil In Coastal Waters,** Vol. 20:4, Fall 1977

Out-of-print issues and those published prior to Winter 1974 are available on microfilm through University Microfilm International, 300 North Zeeb Road, Ann Arbor, Michigan 48106.





Oceanus

(ISSN 0029-8182)
WOODS HOLE
OCEANOGRAPHIC
INSTITUTION
Woods Hole, MA 02543
Postmaster: Please Send
Form 3579 to Above Address

SECOND-CLASS
POSTAGE PAID
AT FALMOUTH, MASS.,
AND ADDITIONAL
MAILING POINTS

Our Dynamic Coastline

by David G. Aubrey

The coastlines of the world represent one of the most variable and complex regions of our globe. They form the unique interface between the earth's three major constituents: the land masses, the oceans, and the atmosphere. The oceans and atmosphere are constantly changing, a behavior scientists are diligently trying to decipher. In response to this variability, the coastlines change over a spectrum of time scales, trying to achieve an equilibrium with those forces shaping it. The activity of our shorelines is of great human concern because nearly two-thirds of the world's inhabitants live along the ocean margins.

Considering the variability and fragility of the world's coastlines, we clearly need to understand the forces sculpting shorelines and how these fragile boundaries respond. Our knowledge of the complex interactions between the atmosphere, oceans, and land masses is incomplete. Our ability to predict variability in this system is woefully inadequate at times (the most common example of this is the media weatherman, who opens himself to violent criticism with each broadcast). Coastal zone management must rely heavily on scientific knowledge to be effective in protecting and preserving the nation's shorelines, while minimizing the adverse impact on man and his cultural relicts along the coasts. Only by understanding the dynamic nature of the coastal zone can we intelligently manage the limited and fragile resource separating the continents from the oceans.

Most of our nation's coastline includes a thin border of beach sand or other clastic material, backed by either sea cliffs, more water, or low-lying plains. Stretches of shoreline lacking beaches generally have sea cliffs plunging directly to the water's edge. Both beaches and sea cliffs serve to buffer the continents from the oceans' fury. Some regions are highly successful, others fail alarmingly. Beaches on the south shore of the island of Martha's Vineyard, Massachusetts, are receding at the rate of 3 meters per year. The Atlantic-facing shores of Cape Cod, Massachusetts, are backed by sea cliffs eroding at a rate of 1 meter per year. Lighthouses and other structures have been relocated inland to avoid the tenacious reclamation of land by the sea.

The major forces modifying beaches on a brief time scale are winds, waves, tides, storm surges, and man. On geological time scales, the slow sea-level rise along much of the nation's coast causes beaches to migrate landward and to contract. Hurricanes and winter storms provide vivid demonstrations of the frailty and vulnerability of beaches; this, combined with local sea-level rise, dooms many of our beaches to recede, accelerating coastal damage during hurricanes and storms.

Barrier beaches represent a special type of shoreline, bordered on one side by an ocean, sea, or gulf, and on the other by a protected body of water (Figure 1). These beaches may be completely separated from land, in which case they are called barrier islands. Barriers attached on one side to land are called barrier spits. When completely enclosing an embayment with only a single channel to the ocean, they are known as baymouth bars. In this article, these classifications are implied in the general term barrier beach. The distinction among these different structures is often temporary, as storms often remold shorelines into a different form within a few hours.

All beaches, including barrier beaches, are in many ways similar in their response to nature's forces. Storm waves, most frequent in winter months, erode beaches, whereas more quiescent waves return sediment shoreward and rebuild beaches. Waves approaching at an angle move sand along the beach. This longshore transport may have no net effect on the appearance of the beach, or it may accrete or erode the beach, depending on whether equal or unequal amounts of sand enter

Cliffs of clay at Gay Head, Martha's Vineyard, move back about 3 meters per year through wave action and wind erosion. (Photo by Jan Hahn)

Figure 1. Barrier beach systems are composed of a thin vegetated beach separating a major body of water from a protected bay and adjacent land mass.

and leave a particular coastal stretch. Beaches may be long or short, straight or sinuous, depending on the forces modifying them and the available sediment. Two major processes are unique to barrier beaches: tidal inlet changes (both their formation and migration), and overwash processes. During storm conditions, these processes can control the poststorm barrier beach configuration, far outweighing other agents that are modifying the beach at that time.

Geological Factors

The shape and characteristics assumed by a stretch of coastline reflect a myriad of geological forces and present-day processes. A major geological factor controlling shoreline features appears to be plate tectonics (see *Oceanus*, Vol. 17, No. 3), which influences the width and bathymetric detail of the continental shelf as well as the local rise or fall of sea level. The rate of denudation of inland regions coupled with the supply of sediment to the coastline are other factors. The local conditions of some shorelines mirror river drainage patterns, faulting, and slumping, as well as biological processes (such as on coral beaches or mangrove beaches). Wind patterns, climate, and tidal range all contribute to the complex nature of shorelines.

Sea-level changes, both eustatic (worldwide) and local, play an important role in long-term beach development. A eustatic sea-level change results from glacial activity; as glaciers melt, worldwide sea level tends to rise, while as glaciers enlarge, worldwide sea level tends to fall. Since the world is currently in an interglacial period, sea level is relatively high. A schematic sea-level curve for the eastern United States (Figure 2) shows a sea-level stillstand near 15,000 years before present (BP), followed by a relatively rapid rise up to 5,000 years BP, when sea level was approximately 5 meters below the present level. Sea-level rise since then has averaged approximately one millimeter per year, gradually encroaching on the continents.

Superimposed on the eustatic sea-level curve are other sea-level fluctuations that result in nonuniform rates of relative sea-level rise around the world. The primary forces causing noneustatic relative sea-level changes are tectonism (such as along the Pacific coast), glacial rebound resulting from land masses gradually readjusting to removal of glacial loading (such as in Scandinavia), and seasonal changes in sea level that are the result of freshwater inflow and heating and cooling cycles in the ocean (steric effects). Tide gauge records from the United States over the last 40 years show the entire mainland coast submergent relative to the oceans, with rates ranging from 3 millimeters per year in New England to about 15 millimeters per year

Figure 2. A sea-level curve for the last 35,000 years clearly shows the rise and fall of sea level associated with worldwide glaciation. (After Milliman and Emery, Science *1968)*

along the Gulf coast. Clearly both eustatic and local effects are important factors in determining relative rates of sea-level rise, and the ultimate fate of beaches.

Nearshore Hydrodynamics

Besides the geological factors, water motions impinging on beaches in large part control the behavior of the shoreline. The major events modifying beaches are hurricanes and winter storms. Hurricanes often have dramatic effects on coastal regions, bringing with them large waves, storm surges, and devastating winds. Hurricane Frederic in September, 1979, caused approximately $1 billion in damages along the Gulf coast (see page 47). The last major hurricane to devastate the Atlantic coast was Donna in 1960. Many coastal and atmospheric scientists believe a major hurricane will strike a populated U.S. coastal region in the next few years, and will surely cause widespread damage.

Winter storms also are responsible for extensive coastal destruction, often affecting much greater stretches of coastline than a single hurricane. Large waves, winds, and storm surges are also associated with these winter storms. The Ash Wednesday storm of March 7, 1962, caused millions of dollars of damage along the eastern seaboard. Each year, nearly a hundred such storms along the U.S. coast shape and modify the beaches.

The mean circulation in the nearshore zone can be schematically represented by a generalized circulation cell (Figure 3). Waves approach the shore at an angle, driving a longshore current in the direction of wave propagation, interrupted periodically by seaward-flowing rip currents. This simple model illustrates the major components of nearshore circulation, but obscures the complexity of the mutual interactions of these various flow fields. To understand how a beach responds to a hurricane, storm, or calm-weather wave field, we

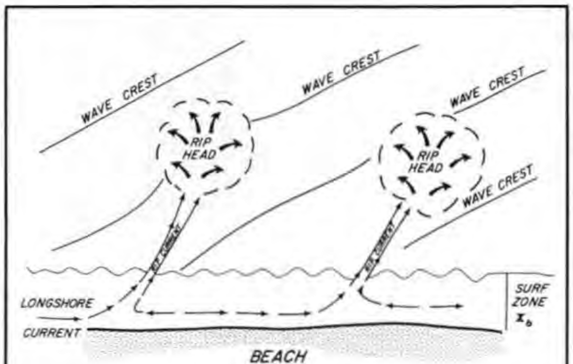


Figure 3. Nearshore circulation cell consisting of incident waves, wave-driven longshore currents, and seaward-flowing rip currents.

first need to know how waves behave as they approach the shoreline.

Surface gravity waves, which are the waves we observe on the sea surface, are fueled by winds blowing over the oceans. As waves propagate across the open ocean, they lose some energy, but can remain coherent over distances of thousands of miles. Once the waves reach shallow water,* however, they begin to transform and lose energy more rapidly. The loss of wave energy in shallow water is primarily through bottom friction; as waves pass over the bottom, energy is dissipated in the bottom boundary layer. Some of the dissipated energy results from moving sediment, the rest goes into the production of turbulence which eventually is dissipated as heat.

The bottom boundary layer is the transition region near the seabed where the wave and current motions decay to zero. The detailed structure and dynamics of this boundary layer are as important as they are complex; to understand the mechanics of near-bottom sediment transport (both bedload, which is material transported along the bed, and suspended load, which is material transported off the bed), we must improve our modeling of the boundary layer.

The changes that waves undergo as they move shoreward or shoal are complex and not entirely understood. The simplest transformation predicts no changes in wave symmetry or period, only changes in height and wavelength. Except for dissipation, a shoaling wave conserves its rate of flow of energy (energy flux) from deep water up to the breaker point. As it shoals, the wavelength constantly decreases; since the period remains the same, the wave speed (wavelength divided by period) also decreases. The wave height initially decreases as shoaling occurs, then increases shoreward. This linear shoaling model predicts symmetrical wave forms and symmetrical near-bottom wave motions.

Waves can change direction as they move shoreward; this phenomenon, called wave refraction, is analogous to optical refraction. As waves propagate into shallower water, their direction changes such that wave crests become more parallel to shore; in very shallow water waves break nearly parallel to the shoreline. Other wave shoaling effects are diffraction and reflection, where the seafloor changes the wave properties because of sudden bottom irregularities, steep bottom slopes, or longshore bathymetric discontinuities.

Field observations show that the linear shoaling model does not adequately represent

*Shallow water here is roughly defined as water depth less than half the deep-water wavelength, approximately 175 meters for a 15-second wave or 38 meters for a 7-second wave.

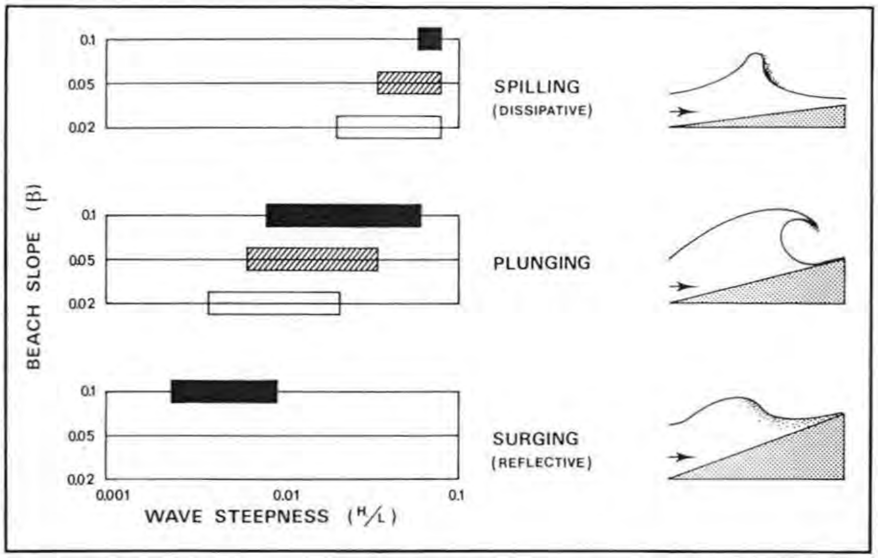


Figure 4. The three primary types of breaking waves are classified according to beach slope and wave steepness (wave height divided by wavelength, H/L). The breaker type influences the nature of water and sand motions near the surf zone.

shallow-water wave behavior. As waves progress shoreward, they steepen and become asymmetrical, with steep, high crests and broad, low troughs. Wave orbital motions become asymmetrical as well, imparting unequal movement to sediment in the onshore and offshore directions, resulting in a net movement of sediment or a finite beach slope. The description of nonlinear wave shoaling, with increased wave asymmetry and transfer of energy between waves of different periods, is of supreme importance in nearshore sediment transport; studies are under way to model and observe this process more thoroughly.

The shoreward propagation of waves is accompanied by variations in the momentum of water waves as well as changes in energy. The resulting force, termed the radiation stress, has widespread ramifications for nearshore processes. Wave set-up and set-down are two results of this radiation stress. As waves shoal, there is an initial slow decrease in wave height, followed by more rapid increase in wave height up to the breakpoint (if dissipation is low enough).

Accompanying the increase in wave height is a tilting of the mean water level down toward the shoreline; this is wave set-down. If the waves were absent, this effect would not occur. Landward of the breaker zone, the wave height decays toward shore; this decay is accompanied by an increase in the mean water level in the swash zone known as wave set-up. Again, this effect is the result of the presence of waves. Wave set-down does not have profound ramifications in beach stability; wave set-up is important, however, as it contributes to the maximum water levels reached during storms and can increase erosion. Radiation stresses also are responsible for generating longshore currents; these are strong currents (up to 2 meters per second) moving parallel to the coast in the direction of wave advance, confined in most part between the breaker point and the shore.

The most dramatic phase of wave shoaling is wave breaking, when the wave becomes so steep and asymmetrical it is unstable. The breaker type is dependent on beach slope and wave steepness (wave height divided by wave length — see Figure 4). Spilling breakers occur with shallow beaches and steep waves, surging breakers occur with steep beaches and waves of low steepness, while plunging breakers result from steep beaches and waves of intermediate steepness. The steepness of the beach has a direct influence on nearshore hydrodynamics, and consequently on beach sand movement. This influence has two major expressions: it affects the transfer of energy from wave motions to long-period motions in the surf zone; and it correlates with run-up patterns in the surf zone.

Field observations have shown that energy is transferred from incident wave periods to long-period motions within the surf zone. This transfer shows up in surf zone measurements of both run-up of waves on beaches and of swash velocities. This transfer of energy could have several causes; one might be the excitation of long-period waves by incoming swell. Theoretical work has demonstrated the possibility of taking energy from incoming surface waves and pumping it into longer-period fluctuations called "edge waves." These edge waves have a longshore periodicity and amplitudes decaying exponentially offshore, whose energy is trapped against the shoreline by refraction. Energy is supplied by incoming ocean waves, and is lost through bottom friction or other dissipation.

Field and laboratory observations are consistent with theories about nearshore edge waves, suggesting their importance in nearshore sand movement. These longshore periodic waves may influence rip current formation and even the beach configuration itself.

Storm systems affect beaches other than just through waves. Storm surges can raise the mean water level near the coast, enabling destructive waves to erode the beach at higher and higher levels. Storm surge is composed of several components. The first is an "inverse barometer" effect, where sea level rises in response to lowered atmospheric pressure associated with storms. A drop in atmospheric pressure of 2 millimeters of mercury is equivalent to a sea-level rise of 3 centimeters. Combined with this barometric effect, a wind blowing onshore during a storm can raise sea level by several meters. The combined storm surge can significantly contribute to storm damage along coasts, and the development of overwashes and inlets along barrier beaches. Other water motions also may influence beach processes, but generally to a lesser degree. Internal waves, shelf circulation patterns, Gulf Stream eddies, and other low-frequency motions may influence any particular beach in an intricate fashion.

Beach Response

Our understanding of how beaches respond to waves and tides is largely empirical, although significant theoretical advances have increased our knowledge of the physics of sediment transport. The U.S. National Oceanic and Atmospheric Administration's Sea Grant program recently has been sponsoring a major effort to better understand how beaches work; this program is called the Nearshore Sediment Transport Study (NSTS). Approximately 10 scientists serve as principal investigators on this project, designed to "perfect relations for the prediction of sediment transport by waves and currents in the nearshore environment." The study emphasizes field measurement of nearshore wave and current behavior at three different sites, as well as theoretical and empirical modeling of surf zone hydrodynamics and sediment transport. This study is contributing to our understanding of the behavior of different beaches as they are exposed to various driving forces.

Although beaches change in a complex manner, some aspects of their behavior can be correlated with particular aspects of the forcing conditions. The most obvious example is the gradual encroachment of the sea onto beaches, responding in part to local sea-level rise. As sea level rises, beaches retreat landward, often leaving peat deposits, tree stumps, and other coastal forest remnants exposed on the open-ocean beaches. Accompanying this shoreward migration may be a narrowing of the beaches and consequently a reduction in their capacity to act as buffers to ocean storms and waves. This beach retreat and narrowing is not a result of sea-level rise alone; it also reflects fluctuations in the availability of sediment in the nearshore zone as well as variations in storm and wave climates.

The movement of sediment along a beach is conveniently divided into on/offshore sand transport and longshore sand transport. Although this division is arbitrary and ignores the very real mutual interactions between these modes, on/offshore and longshore transport do respond generally to different features of the incident wave field. Both modes of transport can be responsible for patterns of beach erosion or accretion at a particular location; it is important to distinguish which mechanism is responsible for coastal change whenever shoreline stabilization methods are considered.

On/offshore transport results from shoaling asymmetrical waves, moving sediment both landward and seaward, alternately acting with and against the influence of gravity. Wind- and wave-induced currents within the surf zone may modify this transport pattern. Field and laboratory experiments suggest that long, low waves build up a beach to a "berm profile," whereas steep, short waves erode the beach face, causing a "bar profile." Since coastal wave climates have a seasonal variability, beach changes also have a seasonal character to them. To better understand the mechanics of on/offshore sediment movement, we need to better understand nonlinear wave shoaling, nonlinear surf zone energy transfers, wave breaking phenomena, wave boundary layer structure, and the bedload/suspended sediment transport transfer functions.

As waves approach and break along a shoreline at an angle, driving a longshore current within the surf zone, sediment moves alongshore in the direction of wave advance. Surf zone structures and tidal inlets interrupt this littoral drift, causing modifications of downdrift beaches. If more sediment enters a coastal area than leaves through longshore transport, the beach accretes. If more longshore drift leaves an area than enters, erosion results. There are many notable examples of longshore sand starvation caused by structures, and the subsequent beach erosion (Figure 5).

Tidal inlets interrupt littoral drift, forcing sand to bypass either by moving in and out of the inlet, or along an offshore delta. When new inlets are formed during storms, sand is taken from the nearshore sand budget to build flood and ebb tide deltas. Once these features are well developed, bypassing of sediment to the downdrift barrier beach can occur by natural processes. If the inlet is modified by jetties, bypassing may be more difficult and often must be accomplished by further human intervention.

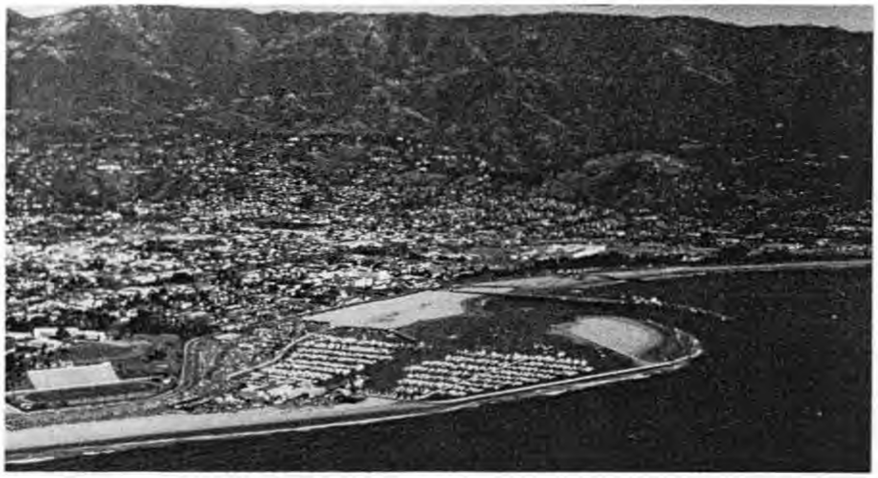


Figure 5. Santa Barbara, California, presents a notable example of longshore sand entrapment by a coastal structure and resultant severe erosion of downdrift beaches.

Storms can damage coasts severely over very short time intervals. Because of the larger wave energies present during storms, much more sand is moved than during quiescent conditions, both alongshore and on/offshore. The effects of rapid storm erosion were measured at Santa Barbara, California, in February, 1980, by the author and R. J. Seymour of Scripps Institution of Oceanography, as part of the NSTS (Figure 6). Vertical beach changes of up to 2.5 meters occurred over a period of several days. In contrast, the recovery of the subaerial beach to its prestorm configuration will take months or years, emphasizing the mismatch of time scales for erosion and accretion of beaches.

Storms acting on barrier beaches often modify them by two additional processes: overwash and inlet formation (Figure 7). Overwash occurs when the combined effects of erosion, wave set-up and run-up, and storm surge, cause the water to overtop the barrier beach, channeling sand and water into the bay. The overwash process has several major effects. It helps to push sand shoreward, causing the barrier to migrate toward shore. It also destroys the protective dune structure and vegetation, thereby temporarily weakening the barrier and making it more susceptible to future overwash events. Finally, it partly fills the bay (hence reducing the volume of water exchanged by the bay and ocean through tides), and can kill existing vegetation and shellfish.

Tidal inlets, or breakthroughs, can be formed on barrier beaches during storms, often as a result of overwash events. These new inlets can change the flushing characteristics of bays, as well as interrupt longshore sand transport, robbing the nearshore of valuable protection. Inlets may remain open for long periods of time, either coexisting with or replacing former inlets. In many cases, storm inlets close after a short period, leaving tidal flushing to the prestorm inlets. These two processes are instrumental to the shoreward migration and evolution of barrier beach systems; their long-term benefits partly offset the immediate removal of sand from the local sand budget.

In addition to the general on/offshore and longshore transport of sand, nearshore water motions also result in the creation of periodic beach forms; this periodicity may be in either the longshore direction (oblique forms) or shore normal direction (parallel forms). These periodic bed structures most likely result from a periodicity in the driving forces; researchers have been only partly successful in isolating the mechanisms generating these features. One common type of periodic form is the multiple parallel offshore bar (Figure 8): these forms have wavelengths of tens or hundreds of meters and heights of approximately one meter. As with most nearshore features, multiple parallel bars can be formed in a number of ways. One documented sequence consists of the

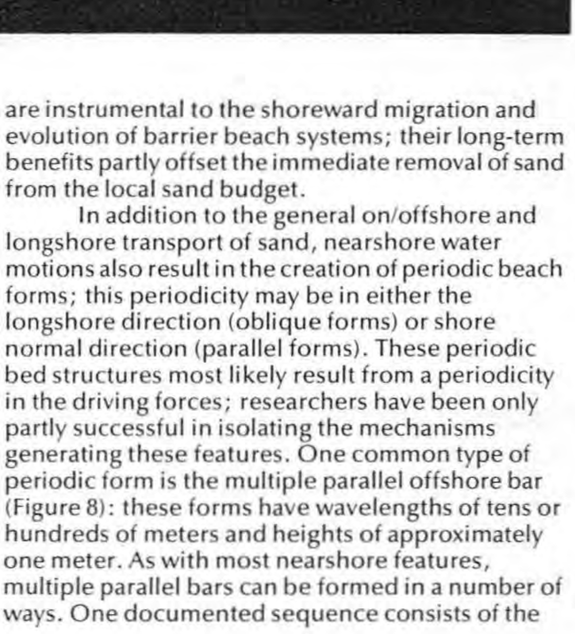


Figure 6. Beach erosion resulting from a series of storms battering Santa Barbara, California, in February, 1980, causing vertical cuts in the beach of up to 2.5 meters, and horizontal beach retreat of up to 60 meters.

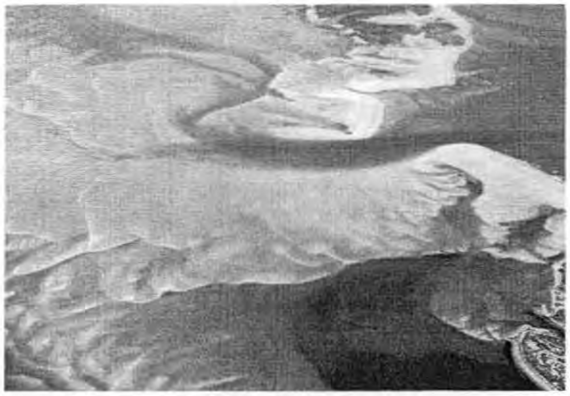


Figure 7. Overwash event and inlet formation occurred in February, 1978, on Monomoy Island, Massachusetts, separating a barrier island into two distinct islands. Strong tidal flows between the Atlantic Ocean and Nantucket Sound keep the inlet open.

Figure 8. Multiple parallel offshore bars located off Truro, Cape Cod, Massachusetts, along Cape Cod Bay, where the tidal range is approximately three meters. The bars intersect the shoreline to the north where they become sinuous; bar spacing increases with distance offshore.

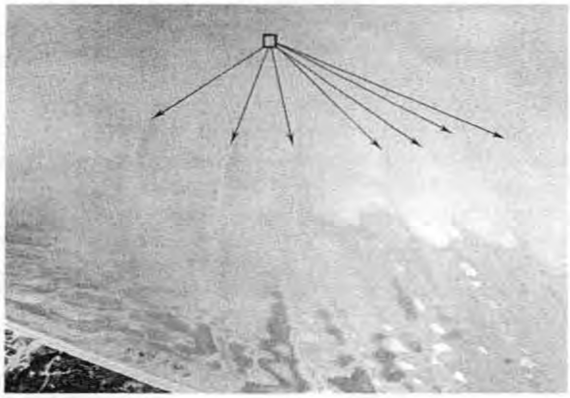


Figure 9. Multiple oblique nearshore bars are superimposed on numerous, smaller-wavelength parallel bars off Wellfleet, Cape Cod, Massachusetts, where the tidal range in Cape Cod Bay is approximately 3 meters. The spacing between oblique bars is several hundred meters.

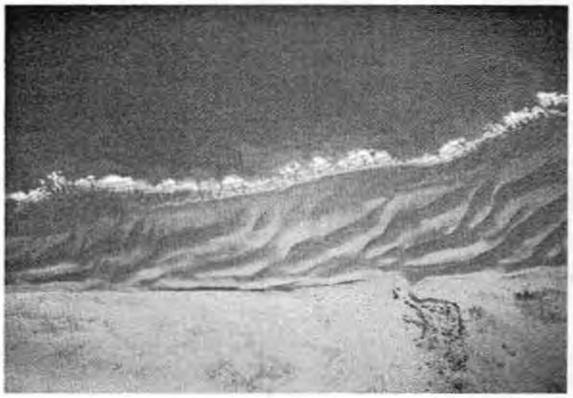


Figure 10. Multiple bars exposed at low tide off El Golfo, Sonora, Mexico, in the Gulf of California, where the tidal range is approximately ten meters. The bars form a confused pattern with both oblique and parallel bars separated by short distances.

formation of a submerged bar under a breaking wave (a breakpoint bar), which moves shoreward under favorable conditions, eventually to weld onto the shoreline as an accretionary feature. As one bar is migrating shoreward, a second breakpoint bar may form, which in turn migrates shoreward. This sequence occurs in both tidal and tideless seas, although it is more common in the latter.

Multiple oblique bars also exist along coastal regions (Figure 9). Their existence is often ascribed to shallow longshore tidal currents; they can exist superimposed on multiple parallel bars that may be wave related. Sometimes oblique bars and parallel bars of the same scale cover the same coastline (Figure 10); although wave forcing is believed responsible for this feature, tidal flows are often contributory (the tidal range in Figure 10 is approximately 10 meters). Crescentic bars often form offshore, with distinct cusps and horns. Their occurrence has been linked by A. J. Bowen and D. L. Inman (1971) to standing edge waves trapped between two longshore features (such as headlands). The region (see introductory photo) has no apparent trapping mechanisms, so other forcing may control the spacing and occurrence of these crescentic bars.

Other longshore periodic features of similar spatial scales include shore-attached hooked bars, with hooks pointing in the direction of longshore transport (Figure 11). The hooked ends of the bars are in the zone of most active longshore transport, averaged over a tidal cycle. These features originally may have been bars separating longshore periodic rip currents. If the shore-attached hooked bars result from periodic rip currents, then the origin of periodic rip currents needs to be explained.

Edge waves are frequently blamed for many of these longshore periodic bedforms. Indeed, R. Dolan, B. Hayden, and C. Jones (1979) have even postulated large-scale edge waves as sculpting the numerous false capes along the eastern seaboard. R. T. Guza and Inman (1975), among others, have suggested subharmonic edge waves as a generating mechanism for beach cusps, with some field evidence to support this association. Edge waves are convenient because they have a longshore periodicity and have an infinite number of modes (hence wavelengths). It is straightforward to match the spacing of any longshore periodic feature to some edge-wave mode. Carefully planned, well-instrumented experiments are needed to assess the role of edge waves and other long waves in nearshore hydrodynamics. Other alternative mechanisms, such as surf zone instabilities, need to be explored in greater detail as well.

Figure 11. Multiple, shore-attached hooked bars stretching from Provincetown, to points further south along the Atlantic shore of Cape Cod, Massachusetts. The hooks point in the direction of longshore transport, and occur with a spacing of hundreds of meters.

A Look to the Future

The beaches of the United States, which include the most extensive barrier beaches in the world, constitute a valuable and delicate resource that must be managed intelligently to avoid loss of their recreational benefits, storm protection, and aesthetic appeal. Beaches are complex systems: they are forced by complex atmospheric and oceanic behavior and respond in an equally complex manner.

Our scientific understanding of beaches in some respects is not sufficient to meet the requirements of coastal zone management in establishing beach policies and guidelines. Active research in beach processes in general, including barrier beach systems, must continue in order to fill this need. In addition to continued research, the scientific community must work closely with the public, educating them and communicating the various scientific alternatives available for managing our nation's beaches. The public in turn must become concerned and better informed if we wish to most effectively and least destructively utilize our valuable beaches.

David G. Aubrey is an Assistant Scientist in the Department of Geology and Geophysics, Woods Hole Oceanographic Institution.

All photos taken by the author, unless otherwise noted.

References

Bowen, A. J., and D. L. Inman. 1971. Edge waves and crescentic bars. *Journal of Geophysical Research* 76: 8662-71.

Dolan, R., B. Hayden, and C. Jones. 1979. Barrier island configuration. *Science* 204: 401-402.

Dolan, R., B. Hayden, and H. Lins. 1980. Barrier islands. *American Scientist* 68: 16-25.

Guza, R. T., and A. J. Bowen. 1975. The resonant instabilities of long waves incident on a beach. *Journal of Geophysical Research* 80: 4529-34.

Guza, R. T., and R. E. Davis. 1974. Excitation of edge waves by waves incident on a beach. *Journal of Geophysical Research* 79: 1285-91.

Guza, R. T., and D. L. Inman. 1975. Edge waves and beach cusps. *Journal of Geophysical Research* 80: 2997–3012.

Inman, D. L., and C. E. Nordstrom. 1971. On the tectonic and morphologic classification of coasts. *Journal of Geology* 79: 1-21.

Wright, L. D., J. Chappell, B. G. Thom, M. P. Bradshaw, and P. Cowell. 1979. Morphodynamics of reflective and dissipative beach and inshore systems: Southeastern Australia. *Marine Geology* 32: 105-140.