they waited for an hour before each run to give the system time to settle. The flow was imaged by monitoring the reflection off anisotropic platelets that had been dispersed in the water (see figure 1b).

Water injected into the pipe gets pulled along by the flow; how far an injected pulse got carried along the length of the pipe turned out to be a key parameter affecting the system's response. When the Manchester group plotted their threshold data against the spatial length of the perturbation, the results for different *Re* collapsed onto a single curve. The threshold depended sharply on that length for short pulses, for which larger amplitudes were needed; otherwise the disturbances decayed as the injected pulse traveled down the pipe. The threshold amplitude for perturbation lengths longer than about six pipe diameters became independent of length.

For comparison to theory, the natural means of describing the threshold amplitude is the volume flux of the perturbation normalized by the flux in the pipe. When plotted this way, the threshold amplitudes showed an inversely proportional dependence on *Re*—that is, a scaling exponent γ of –1, as seen in figure 2. That scaling relationship extends over an order of magnitude in *Re*, from 2000 to nearly 20 000. "What's interesting is that the scaling looks so clean at relatively low Reynolds number," comments Rich Kerswell of the University of Bristol. The scaling exponent of –1 agrees with calculations by Chapman, based on the growth of transient fluctuations, but it's not yet clear whether that mechanism is what's at work in the Manchester experiments.

The nature of the transition

Of course, determining the size of the kick needed to drive a flow turbulent is only one part of understanding the turbulence transition. The mechanism by which the turbulent state develops is also vital to a full understanding.

The laminar flow state can be viewed as an island (or, technically, a basin) of stability in the sea of phase space. The Manchester work has measured how the island size decreases as *Re* increases. But what happens when a sufficiently strong perturbation knocks the system off the island?

A mathematical solution to that question may be emerging. Fabian Waleffe of the University of Wisconsin-Madison has formulated a so-called self-sustaining process that leads to nonlinear, three-dimensional traveling-wave solutions of the Navier–Stokes equations for plane Couette and plane Poiseuille flow.[5] Holger Faisst and Bruno Eckhardt of the University of Marburg[6] and Hakan Wedin and Kerswell at Bristol[7] have recently reported a class of similar traveling-wave solutions in pipe flow.

Those solutions, one of which is shown in figure 3, have a discrete number of faster-moving streaks of fluid near the wall and slower streaks near the center, and vortices around which the fluid spirals as it travels down the pipe. Hof, now with Frans Nieuwstadt at the Delft University of Technology, has found some evidence for such states in pipe flow. Although the traveling-wave flow states are unstable, they may represent the first indications of increasing complexity in phase space, which ultimately harbors a turbulent attractor as *Re* increases.

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Sea-Level Rise Exacerbates Coastal Erosion

A recent analysis of more than a century's worth of data forebodes severe losses of coastal land.

On 7 March 1962, what became known as the Ash Wednesday Storm struck the mid-Atlantic coast of the US. Boosted by a high spring tide, the storm's waves grabbed sand normally out of reach and dumped it in offshore shoals. In Delaware, the storm pushed the shoreline back 80 meters.

Today, Delaware's beaches have largely recovered, thanks to the steady action of long-wavelength waves that move sand from shoals to beaches. This take-and-give plays out on beaches all over the world. It's responsible for the remarkable longevity of barrier islands and, indeed, for the formation of beaches in the first place.

Short-term local recoveries, however, belie a protracted global trend. At least 70% of the world's beaches are in what seems like permanent retreat. An increase in storminess or a decrease in replenishment could be responsible for the long-term loss, but meteorological records of the past century evince no such changes.

Instead, as Keqi Zhang, Bruce Douglas, and Stephen Leatherman of Florida International University demonstrate in a forthcoming paper, the culprit appears to be sea-level rise.[1] As Earth's climate warms, seawater expands and long-frozen glaciers and ice caps shed meltwater into the ocean. The most recent estimates put the mean global increase in sea level at 1.5–2.0 millimeters per year.[2] Sea-level rise doesn't by itself erode beaches. Rather, it acts like a gradual, relentlessly swelling tide that extends the destructive power of storms.

That finding might not seem surprising. However, the FIU researchers have also vindicated a 42-year-old model that quantifies the relationship between sea-level rise and erosion. Formulated by pioneering coastal engineer Per Bruun, the model makes a grim prediction for the sandy beaches of the US East Coast and elsewhere: Without expensive remedial action, each centimeter of sea-level rise will be accompanied by a loss of about a meter of beach. Within a century, oceanfront properties, like those in figure 1, could end up literally at the front of the ocean.

Shifting sands

Quantifying the relationship between sea-level rise and erosion isn't easy. The short-term movement of sand perpendicular to the shoreline (cross-shore) is much stronger than any change associated with sea-level rise. And at many beaches, the movement of sand parallel to the shore (longshore) is much stronger than in the cross-shore direction.

Like the physicist's spherical cow, Bruun's 1962 model sweeps those difficulties under a rug of simplification.[3] His starting point is an ideal beach that has no longshore transport. He defined a closure depth D_C below which waves lack the energy to shape

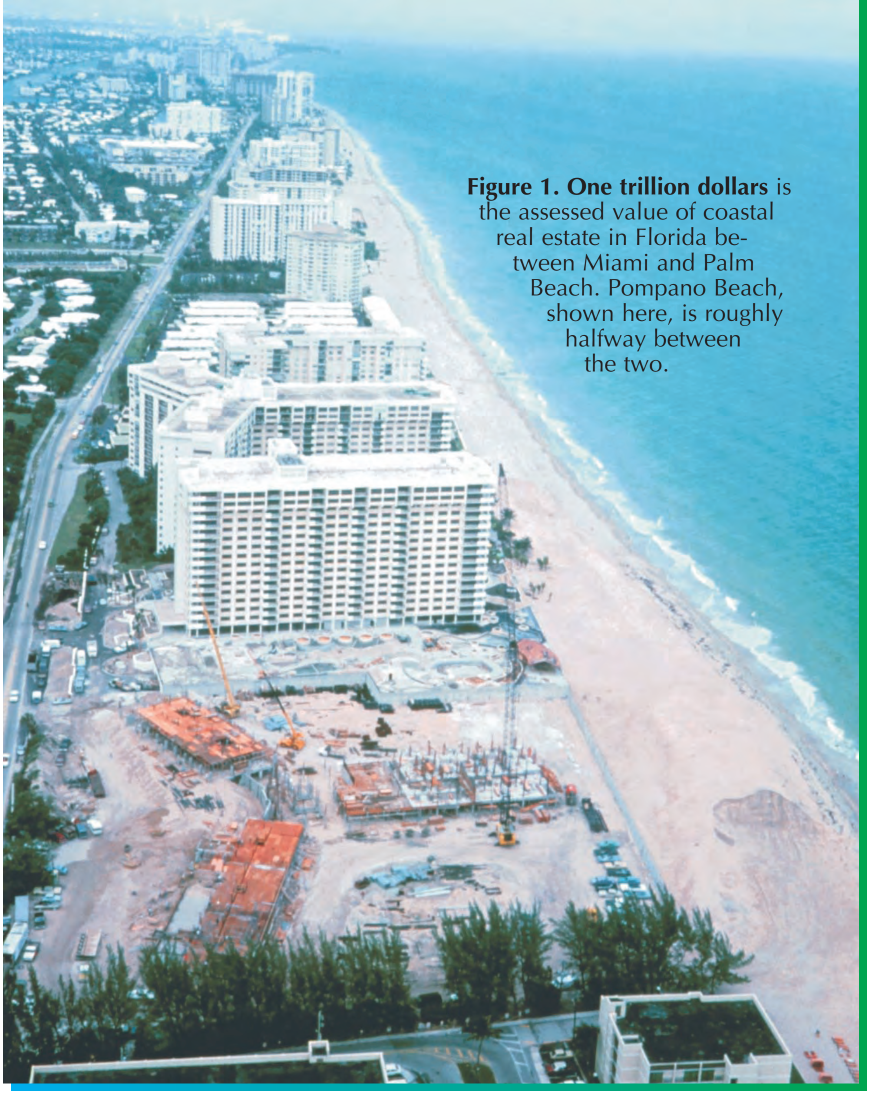

Figure 1. One trillion dollars is the assessed value of coastal real estate in Florida between Miami and Palm Beach. Pompano Beach, shown here, is roughly halfway between the two.

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the sandy sea floor. At shallower depths closer to the shore, the action of waves creates a steady-state profile that extends landward for a distance l up to the berm, the part of a beach where the sloping, sea-washed sand meets the flat, dry sand higher up.

Bruun didn't define or derive the profile. Rather, he looked at how a small rate of sea-level rise, a, perturbs it. His analysis showed that the profile moves up at a rate a and landward at a rate s such that $s/a = l/(D_B + D_C)$. Here, D_B is the height of the berm measured up from the mean sea level and D_C is measured down from the mean sea level.

Because of its underlying assumptions, Bruun's model can't predict the behavior of an individual beach. However, it can reveal how sensitive erosion is to sea-level rise. And because $l/(D_B + D_C)$ lies in the range 50–100 for most beaches, the model can provide coastal engineers and policy makers with a simple formula for predicting the effect of sea-level rise.

Testing Bruun's model involves seeing how s depends on a over a range of values. Fortunately, a varies naturally along the US East Coast. The great ice sheet that overspread North America 20 000 years ago extended as far south as the Chesapeake Bay. When the ice melted, its huge pressure on the underlying earth vanished. Unburdened the earth has been gradually rebounding ever since and contributes a latitude-dependent local term to the rate of sea-level rise (see the article that Douglas wrote with Richard Peltier in PHYSICS TODAY, March 2002, page 35).

Tide-gauge measurements going back to the late 19th century provide the means to determine a. The rate of beach retreat, s, is derived from various sources, including mid-19th-century waterline surveys, aerial photographs, and GPS surveys. For the past 20 years, Leatherman and his collaborators have assembled and digitized those measurements. The resulting database covers the East Coast from Massachusetts to Florida with a typical time span of 150 years and longshore resolution of a few hundred meters.

Bruun's assumption of no longshore transport should apply, on average, to a beach that neither gains nor loses sediment to beaches either side of it. Can one find such a beach on the East Coast?

In the 1960s, J. J. Fisher noticed that the great, sandy beaches of the Eastern seaboard—those of Long Island, New Jersey, the Delmarva Peninsula, and North and South Carolina—share similar morphology.[4] Each of the coastal compartments, as Fisher termed them, is bounded at its ends by deep-water channels and comprises four distinct segments. At the north end of the compartment is a

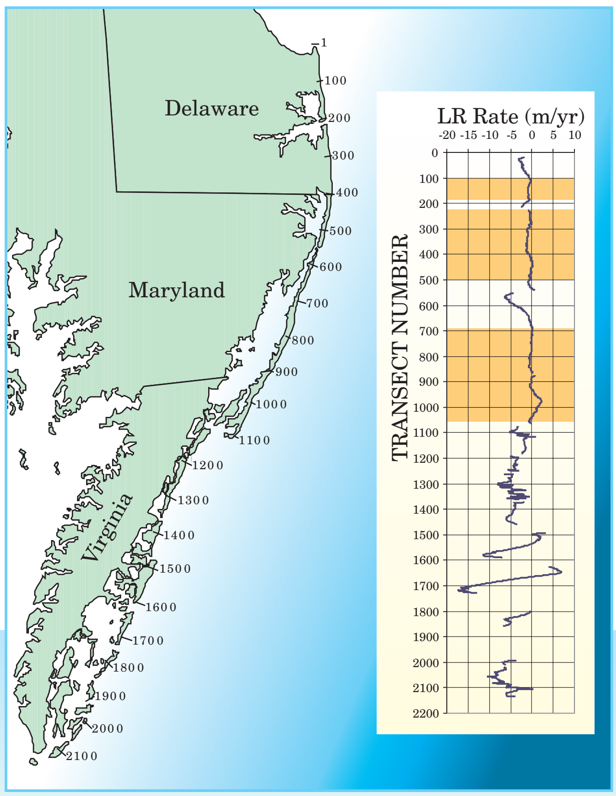

Figure 2. The local recession rate of the Delmarva coast is plotted on the left as a function of shoreline position (transect number). The areas highlighted in yellow correspond to those sections of beach where the assumptions of Bruun's model apply. There, the average rate of shoreline retreat was 0.2 meters per year. (Adapted from ref. 1.)

sandy spit. Next (heading south and west), comes what Fisher called the mainland, which is followed, in turn, by a stretch of coast characterized by long barrier islands. The southernmost of the four segments consists of short barrier islands pierced by inlets.

Thanks to the channels that bound them, the compartments don't exchange sediment with each other. And none is so long that the relative sea-level rise varies significantly along its length. At first, the FIU researchers thought that by averaging a and s over each compartment, they could see Bruun's model in action. They couldn't.

Examining each segment revealed why. The sandy spits change shape and location too quickly for s to be measured reliably at a fixed location. Also problematic are the short barrier islands. Their inlets disrupt the longshore transport of sediment in such a way as to cause an average net loss of beach even without sea-level rise. Coastal engineering projects have a similar effect.

The best data, it turned out, came from the long barrier islands and certain parts of the mainland segments. Figure 2 shows the 40% of the Delmarva coast that qualified for inclusion in the analysis. There, a is 3.83 mm/yr, s averages to 0.20 m/yr, and s/a is 52, which falls within the typical range of $l/(D_B + D_C)$. The other compartments are also consistent with Bruun's model and yield an average from Montauk Point to Hilton Head of 78.

Coastal development

Despite the ocean's persistent encroachment, people continue to build houses on the sandy coasts of the US. The attraction lies, in part, in generous federal flood insurance. The Federal Emergency Management Agency treats coasts like rivers. That is, insurance rates are based on elevation with respect to the 100-year flood line.

But 100 years ago, the mean sea level at the Delaware–Maryland coast was 40 cm lower and the shoreline 20 m farther out to sea than they are now. To their meteorological records, land surveys, and property assessments, prudent policy makers or insurers should perhaps provide a safety margin based on Bruun's model and the anticipated increase in sea-level rise.

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