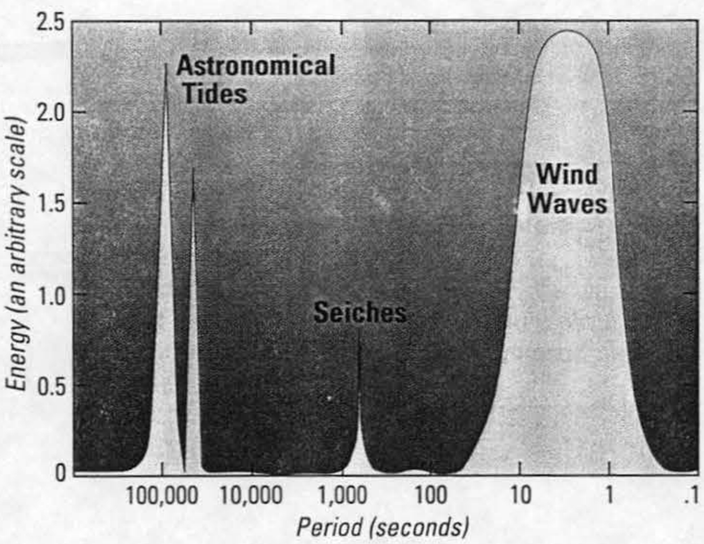
Coastal Seiches

Graham S. Giese and David C. Chapman

Coastal residents associate the sea with particular rhythms: the short, insistent lapping of small harbor waves, or the long beat of ocean swell rolling toward shore from distant storms at sea. The rhythms might be the coming and going of the tides; for some coastal dwellers, these have a daily cadence; for others, the rhythm has two beats each day (see Tides and Their Effects, page 27).

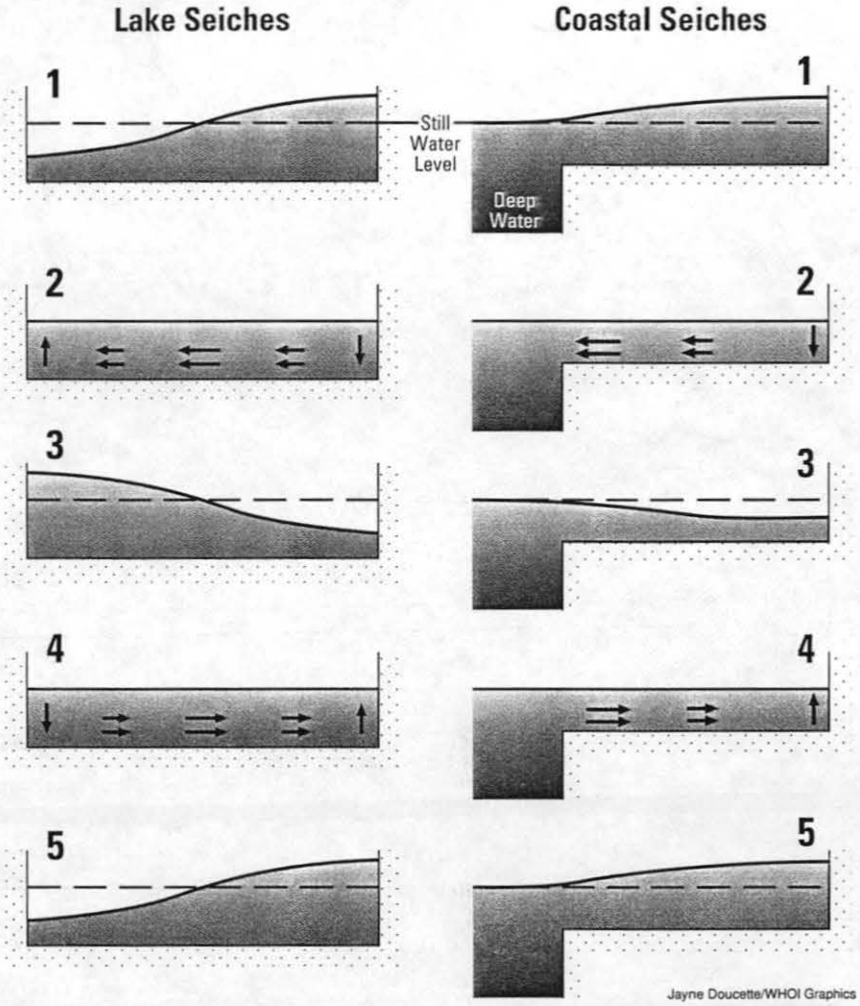
If we plot wave energy on a graph against the period of the waves that occur at a particular coastal location, we expect to see each of these familiar rhythms represented by an energy maximum; a broad plateau in the range from seconds to tens of seconds for wind-generated waves, and high, sharp peaks at about 12 and 24 hours for astronomical tides. In addition, we should not be surprised to see secondary peaks between these expected maxima, peaks of energy representing waves with intermediate periods and produced by other processes.

These secondary peaks were once frequently called "secondary oscillations of the tide," particularly by Japanese scientists. The most common are generally produced by standing waves known as "coastal seiches," which occur at periods ranging from about 10 to 100 minutes. Coastal seiches are typically found in harbors along the exposed coasts of the world. While they are usually small in amplitude compared to local tides, at certain places they can greatly exceed the tidal height and cause considerable destruction. For example, residents of Nagasaki, on the southern coast of Japan, call the half-hourly rise and fall of their harbor's water *abiki*. These coastal seiches can reach heights exceeding 10 feet. Those who live in the Balearic Islands of the western Mediterranean Sea know the local



Coastal wave energy is mostly concentrated at the 12- and 24-hour tidal periods (twin peaks at left of figure) and at the 1- to 10-second periods of wind-generated waves (broad maximum at right of figure). Typically, however, sea-level records from exposed coasts exhibit another energy maximum at periods ranging from 10 to 100 minutes. This energy is largely produced by coastal seiching. Illustrated here is a generalization of the wave-energy spectrum for Ciutadella Harbor on Spain's Menorca Island where the dominant seiche period is 10 minutes.

Jayne Doucette/WHOI Graphics



Seiches are standing waves in basins that produce alternately high and low water levels at the coast and alternately on- and off-shore currents away from the coast. Seiches in lakes (left column) were first studied in the 19th century by F.A. Forel who named the phenomenon after the local term for standing waves in Lake Geneva, Switzerland. Coastal seiches (right column) produce maximum currents at the boundary between shallow and deep water (such as the shelf edge or harbor mouth).

10-minute harbor oscillations as *rissaga*, and they are painfully aware of occasions when the *rissaga* rips their boats from their moorings and tosses them together at the harbor head. Other troublesome seiches occur at Capetown in South Africa, at Los Angeles in the US, and at many other locations along the world's coasts.

Seiches, then, are the source of other rhythms known to coastal people—rhythms specific to certain harbors and bays, rhythms that contribute to the mystery of the sea, and, sometimes, to fear of the sea.

Early Coastal Seiche Studies

What produces these sometimes-destructive coastal seiches? One of the first to propose an answer in the scientific literature was Sir George Airy, Astronomer Royal during the reign of Queen Victoria and well known for his development of the mathematical theory describing small-amplitude water-wave behavior. Airy's contribution appeared in a paper published by the Royal Society of London in 1878 concerning tides at the island of Malta in the Mediterranean Sea. Noting the frequent appearance of 21-minute, sea-level oscillations on the Malta tide records and their similarities to records of lake seiches published in 1876 and 1877 by

F.A. Forel in Switzerland, Airy wrote "The origin assigned by Dr. Forel is, I think, most certain; that they are waves originally caused by winds; but that they are reflected from one side and another of the limited sea, and thus become stationary waves. The waves forming the seiches of Malta are reflected, I suppose, from the shores of Sicily and Africa."

In 1907, a little more than a quarter century after Airy's report, R.A. Harris of the US Coast and Geodetic Survey described similar 45-minute coastal seiches at Guanica Harbor on Puerto Rico's southern coast. Like Airy, Harris ascribed the waves to meteorological forcing—strong winds or sudden changes in barometric pressure—but he rejected the concept that the seiches were due to waves reflecting back and forth across the width of the Caribbean Sea (that is, between the shores of Venezuela and Puerto Rico). Rather he proposed that the oscillating water body consisted of Guanica Harbor itself, together with the island shelf bordering the deep Caribbean Basin.

Coastal Seiches in Puerto Rico

Our seiche studies began in the late 1960s when Graham Giese served on the faculty of the University of Puerto Rico and had an opportunity to extend Harris's sieche observations. He examined 10 years of tide-record data from Magueyes Island, which is just a few miles west of Guanica Harbor, but failed to find any correlation between the oscillations and local winds. He did, however, find a completely unexpected, mysterious relationship between seiches and the moon: Seiche activity was minimum at the new and full moon and maximum at the time of half moon, and the half-moon activity was most extreme when the preceding new or full moon occurred at perigee, when the moon was closest to Earth in its monthly orbit.

This correlation strongly suggested a relationship between Puerto Rico seiche activity and the astronomical tides, specifically the semidiurnal tides because only they, and not the diurnal tides, are tied to the moon's phases. But there were two obvious problems with explaining the seiches as being caused by the tides. First, the semidiurnal tide is practically nonexistent along the south coast of Puerto Rico, and, second, the tidal forces are strongest at the time the seiches are smallest—new and full moon—and weakest at half moon when seiches are largest!

We had a tentative explanation: Seiches were excited by the arrival of internal waves created by tidal currents.

There was, however, evidence of a tidally produced phenomenon offshore of Puerto Rico that could be used as the basis of an explanation that would satisfy the observations: internal tides, or, more specifically, internal waves produced by tidal forces. Internal waves occur in the sea's interior, between layers of lighter upper water and heavier deeper water. They travel much more slowly than comparable surface waves—on the order, say, of 5 miles per hour—so that if large internal waves were formed at new or full moon in the southeastern Caribbean offshore of Venezuela and Trinidad where semidiurnal tides are most pronounced, they would arrive at Puerto Rico about one week later, that is, at about the time of half moon.

Can Internal Waves Possibly Generate Seiches?

So here we had a tentative explanation, a hypothesis, for the seiches: They were excited by the arrival of internal waves created by tidal currents in the southeastern Caribbean about a week earlier. But, was it reasonable to expect that deep-sea internal waves were capable of creating sizable surface waves along the coast? The intuitive answer was no. It was well accepted that strong surface tides along deep-sea margins could produce internal waves, but there was no evidence that the process could be reversed. The accepted pathway for energy transfer was from surface tides to internal waves, somewhat analogous to water flowing downhill.

In 1984, however, David Chapman demonstrated that the process could, in principle, be reversed. Studying a class of coastal surface waves known as "edge waves," he developed a theoretical model showing that deep-sea internal waves impinging upon a steep continental margin could produce coastal edge waves of significant amplitude. In fact, his results indicated that through a process known as "resonant excitation," an example of which might be the proverbial singer shattering a crystal vase, the surface-edge-wave amplitudes could be of roughly the same size as the internal-wave amplitudes.

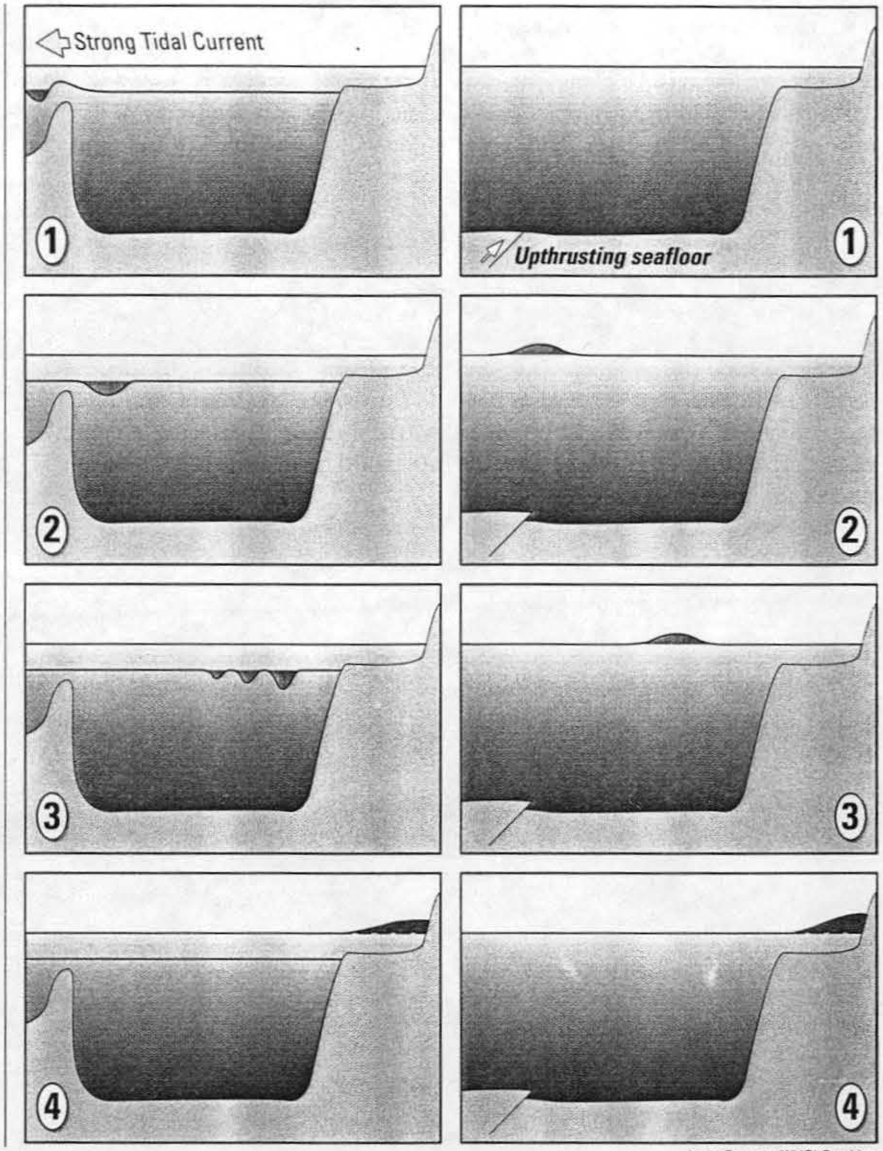
But what about seiches—could the same (or a similar) physical process apply to the generation of coastal seiches by internal waves? This question brought us together. Using the basic theoretical model developed for the edge-wave study and modifying it to match the requirements for coastal seiches, specifically the seiches observed on the Caribbean coast of Puerto Rico, we were able to show that, yes, internal waves of reasonable size arriving at the steep island slope off Puerto Rico could, indeed, produce coastal seiches with the observed characteristics.

Josep Gomes/Courtesy Group of Geophysical Fluid Dynamics, UIB

Large-amplitude coastal seiches can have catastrophic impacts on harbor facilities and small boats. This photograph shows townspeople surveying damage resulting from the large (approximately 2-meter-high) seiches, locally known as rissaga, *that rocked Ciutadella Harbor on Spain's Menorca Island in July 1984.*

Do Internal Waves Actually Generate Seiches?

All right, we agreed, this process is possible, but does it really happen? How could we find out? Here we were fortunate to find help in the work of others. A basic assumption underlying our hypothesis was that tide-generated internal waves are capable of carrying considerable amounts of energy over hundreds of kilometers and many days. This had seemed next to impossible until 1980, when A.R. Osborne (Exxon Production Research Company) and T.L. Burch (EG&G Environmental Consultants)



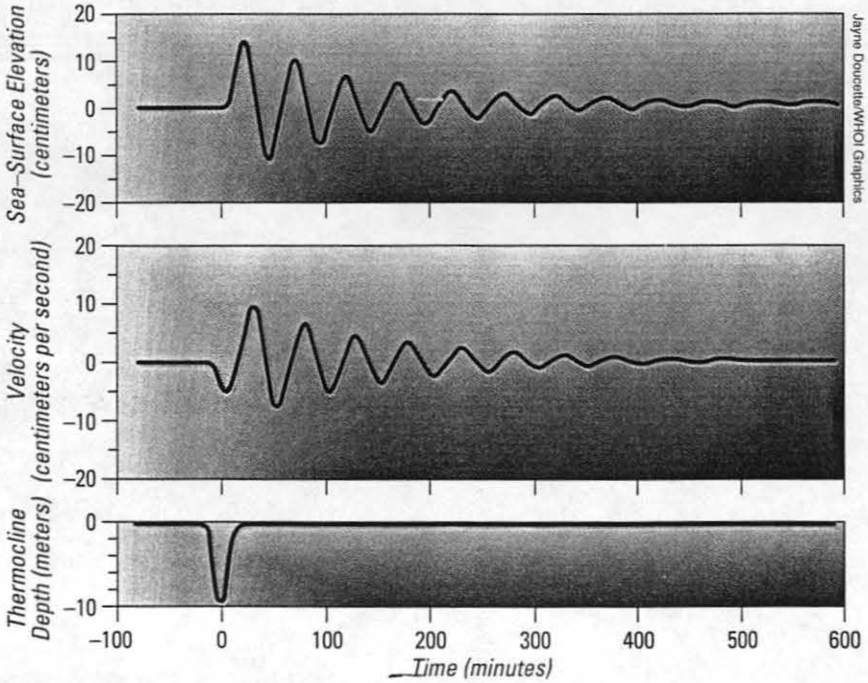
Studies carried out in Puerto Rico and the Philippines support the hypothesis that large-amplitude coastal seiches can be produced by internal waves that have themselves been generated by strong tidal flows of stratified water over shallow banks and ridges. At left, (1) shows an internal "lee wave" being formed by strong tidal currents flowing from right to left. When the tidal current turns (2), the internal wave moves to the right, crossing the ridge to form a broad internal depression. As the internal depression travels away from its source (3), it forms a packet of deep-sea internal "solitary waves." Finally, when the solitary waves reach the coast (4), part of their energy is transferrred to oscillations (seiches) of the coastal water. The total distance traveled by the internal waves may be hundreds of kilometers and may occupy several days. By way of comparison, at right is the related and more-familiar phenomenon known as tsunami, in which deep-sea surface waves caused by submarine crustal disturbances produce seiching in coastal waters. In this case, the total distance traveled may be thousands of kilometers and the travel may be accomplished in hours. While tsunamis may, on rare occasions, produce coastal waves as much as ten times larger than the largest seiches produced by internal waves, the total energy dissipated by tsunamis is much less than the tidal energy dissipated by internal-wave-excited seiches.

provided convincing evidence that large-amplitude, internal, tidal oscillations could exist in the form of "solitary waves" (that is, waves that maintain the almost unchanging form of single troughs for long periods of time), and that discrete packets of such internal solitary waves could travel hundreds of kilometers with little energy dissipation.

Better yet for our purposes, another set of investigators working with John Apel, then with NOAA's Pacific Marine Environmental Laboratories, made a detailed study of internal solitary wave packets that formed at a shallow passage separating the Sulu and Celebes seas in the Philippines and then crossed the entire width of the Sulu Sea to eventually arrive, two and a half days later, at the shores of Palawan Island, some 450 kilometers distant. The opportunity for us was clear: If we could observe seiches along the coast of Palawan, we should be able to tell from the patterns of seiche activity whether or not they were produced by the solitary waves Apel and his coworkers described.

In fact, in 1928 pronounced seiche activity had been reported at Puerto Princesa on Palawan Island by Frank Haight of the US Coast and Geodetic Survey. According to Haight, "The period of this vibration is almost exactly one hour and a quarter...and its amplitude varies from a few hundredths of a foot to 3 or 4 feet." Haight concluded that the seiche forcing could "be traced to atmospheric variations," but he readily admitted that he had insufficient evidence to prove this point.

Supported by an Independent Study Award from Woods Hole Oceanographic Institution (WHOI) and additional funding from the National Science Foundation's International Division, we joined forces with colleagues in the Philippines to establish a tide recorder at Puerto Princesa and to keep it in operation for two years. The Puerto Princesa data provided the supporting evidence we had hoped to find. The harbor experienced the large 75-minute oscillations (seiches) that Haight described; the seiches occurred in fortnightly cycles closely related to the



Results of theoretical modeling demonstrate that a deep-sea internal wave (bottom) arriving at the shelf south of Puerto Rico can produce 50-minute sea-surface oscillations (top curve) and cross-shelf current oscillations (middle curve) similar to those that have been observed.

Seiche Experiments

Using observations to directly test a theory is often very difficult. In the case of coastal seiches excited by internal waves, this would require accurate, simultaneous measurement of the ambient stratification, the incoming internal waves, and the resulting seiches. We would then be left with the problem of examining the observations in a way that removes extraneous processes (such as local currents) that are measured, but are not part of the problem at hand. One alternative is to test the theory by comparing it with controlled experiments in a laboratory. Experiments permit us to study just the process we are interested in. Since experiments can be controlled and varied, they can be used to "exercise" a theory, and find out when it works and, just as importantly, where it fails.

In conjunction with the ocean observations described by Giese and Chapman, we have been using laboratory experiments to test our theory of seiche excitation by internal waves. These experiments are performed in an 18-meter-long wave tank that is divided into two sections—a deep area and an adjoining shallow shelf. The bottom of the deep section is filled with salt water. Fresh water floats above this and over the shelf. Using computers to control the experiment, we are able to generate one internal solitary wave that propagates along the tank, reflects from the shelf wall, and excites shelf oscillations. Probes are used to measure the internal-wave amplitude at a point before the shelf wall and the velocity of the fluid on the shelf. An example of one such run is shown. These results can then be compared directly to theoretical predictions. Because we can easily control the experiment by changing the internal-wave amplitude or the shelf geometry, we can test the theory over a broad range of parameters. But perhaps most importantly, the experiments allow us to study more realistic situations, such as a slope connecting the deep section to the shelf, for which there is presently no theory. In this way, laboratory experiments help us to broaden our understanding of the basic physical processes that may result in severe coastal seiching.

—Karl Helfrich

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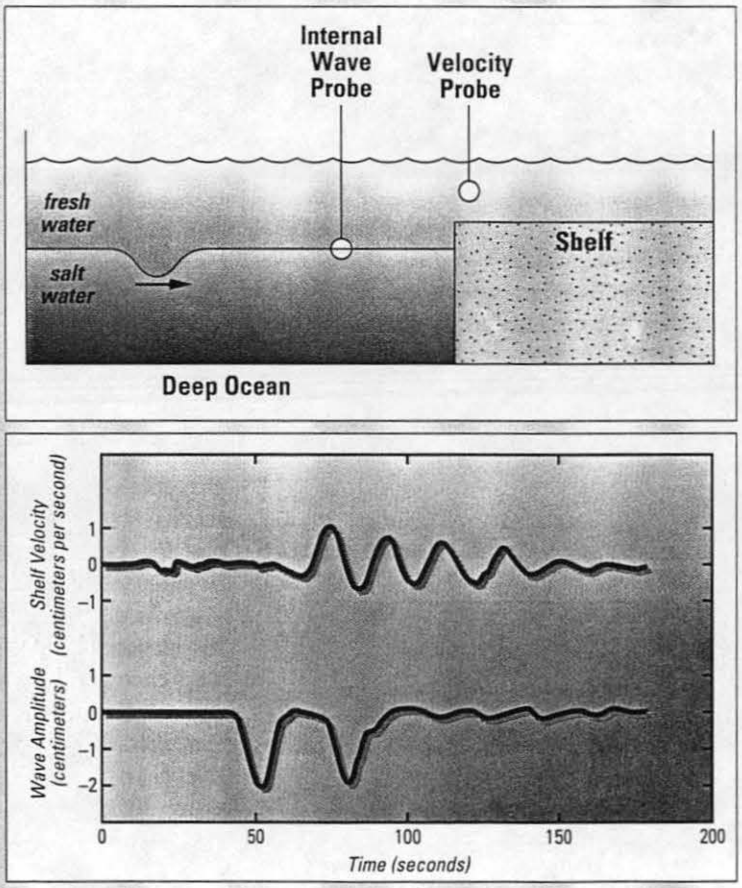
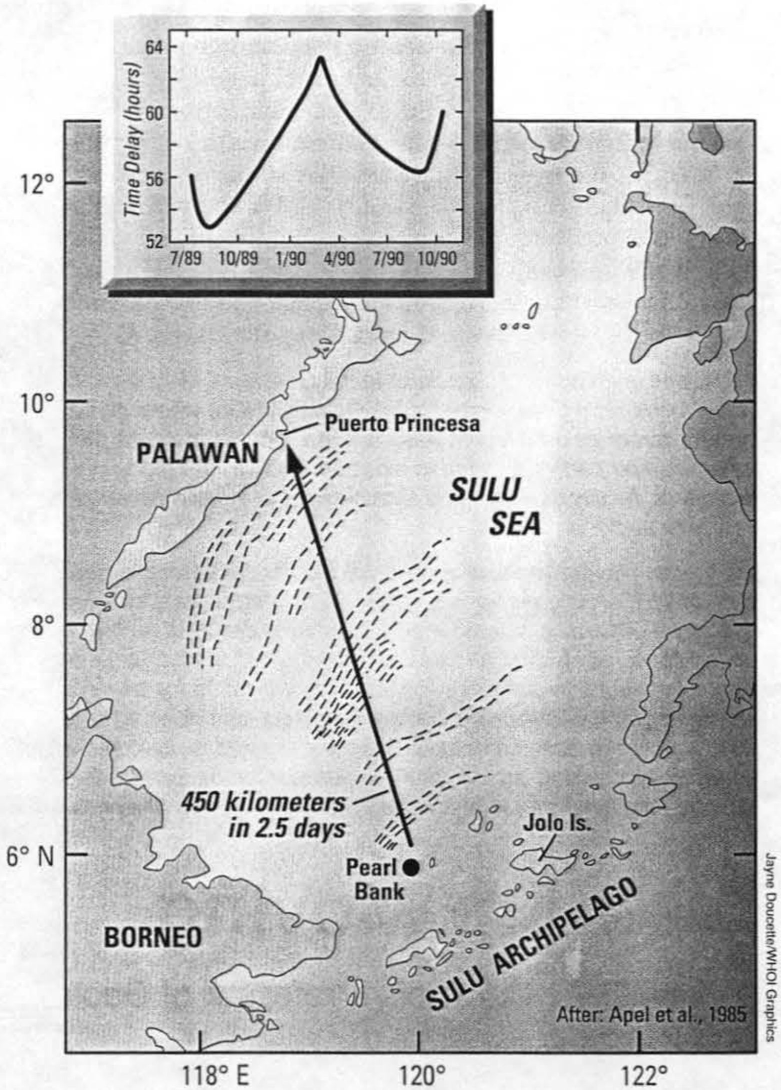


In the wave tank (top), probes measure the amplitude of waves generated and reflected. The two pulses in the internal wave record are the incident and reflected waves.



Satellite images of the Sulu Sea in the Philippines show the surface expression of internal solitary wave packets initially formed near Pearl Bank in the Sulu Archipelago. After about two and a half days of travel, the internal waves reach Puerto Princesa on Palawan Island, where they produce harbor seiches. The inset shows actual delay times observed during the authors' study.

lunar phases; and the largest seiches began about two and a half days following the strongest tidal currents at the passage where Apel's group had shown the Sulu Sea internal waves to be created.

Is This a Common Global Phenomenon?

Our results from Puerto Princesa confirmed our original hypothesis. Yes, internal waves do produce coastal seiches—in some places. But an important question remains: Is this a general phenomenon to be expected wherever large coastal seiches are found, or is it specific to certain locations where large internal waves are known to occur?

The answer is important because though large, unexpected coastal seiches are known to occur in many harbors around the world, at present they can't be predicted and people who may be affected can't be warned. If, however, it can be shown that these seiches are produced by tide-generated internal waves, it is likely that they will eventually be predictable, as the Puerto Princesa seiches now are.

We have support from the Office of Naval Research to explore the general applicability of our work. Using a combination of numerical and laboratory modeling (as described in the box on page 44 by our WHOI colleague Karl Helfrich) and field work at Ciutadella Harbor in Spain (being carried out in cooperation with scientists at the University of the Balearic Islands in Majorca), we are extending our earlier studies in an effort to make them more generally useful, both to scientists and the general public.

How will this turn out? We don't know. But we do know that no matter how many questions are answered, even more will be raised, for there is no indication that the rhythms of the sea will ever lose their mystery to those of us who live and work along the coasts.

Graham S. Giese is a Research Specialist in the Geology & Geophysics Department at the Woods Hole Oceanographic Institution (WHOI), where he began his oceanography career as a Research Assistant in 1956. His meteoric professional advancement can be partly attributed to his years away from Woods Hole as a graduate student, faculty member, and administrator at various universities and marine research stations.

David C. Chapman is an Associate Scientist in the Physical Oceanography Department of WHOI. He grew up in a rural area of upstate New York before attending Cornell University, where he embarked on a career of mathematically modelling the flow of fluids through trees and other green plants. However, a visit to the beaches of southern California convinced him of the many benefits of a career in oceanography. Reasoning that the ocean couldn't differ much from other fluids, the change seemed natural. Despite this slight miscalculation, he thoroughly enjoyed graduate school (and the beaches) at Scripps Institution of Oceanography, and continues to enjoy studying and living near the ocean.