# Seiches



*Transient standing-wave oscillations in water bodies can create hazards to navigation and unexpected changes in water conditions*

Ben J. Korgen

A Louisiana Cajun trapper sits on his porch and listens to country music on his portable radio as he watches the pattern of lights reflect from the glassy-smooth surface of the adjacent bayou. At 9:50 p.m., the music is interrupted by a special bulletin: A major earthquake has hit southern Alaska; scientists believe that it might be one of the biggest of all time.

*Ben J. Korgen is a physical oceanographer at the U.S. Naval Oceanographic Office. He completed his Ph.D. in physical oceanography in 1969 at Oregon State University and then served as a professor at the University of North Carolina at Chapel Hill. Since joining the Oceanographic Office in 1978, he has held an adjunct appointment at Tulane University and has served on the Advisory Committee of the Mississippi-Alabama Sea Grant Consortium. He has published research on terrestrial heat flow and on changing conditions in the benthic boundary layer. His present interest in seiches focuses on unexpected changes in the benthic boundary layer and on removing obstructions to safe navigation. Address: Environmental Products and Studies Division, U.S. Naval Oceanographic Office, Stennis Space Center, MS 39522-5001.*

The trapper surveys his placid domain and is thankful that he lives so far from the danger. But his mouth falls open in disbelief as the bayou surface bulges into a wave the height of an adult man, then boils back and forth in an acoustic backdrop of night fishermen cursing, mooring lines snapping and boats banging together. After the initial chaos, the motion becomes a rhythmic pattern with wave crests that seem to move more up and down than sideways. The rocking motions continue into the night, with their strength diminishing slowly from one oscillation to the next.

This bizarre experience belongs to the world of seiches—the rhythmic, rocking motions that water bodies undergo after they have been disturbed and then sway back-and-forth as gravity and friction gradually restore them to their original, undisturbed conditions. (Seiche is a French word that has become an internationally used scientific term; it is pronounced "saysh.")

Although similar events have occurred at scattered points around the world over the span of recorded history, what the trapper witnessed was highly unusual and provided us with what is probably the best known example of its kind. The event described followed the March 27, 1964, Alaskan earthquake, when seismic surface waves rippling the earth's crust took 14 minutes to move from Prince William Sound, Alaska, to the Gulf Coast region of Texas and Louisiana, where they triggered innumerable seiches in bays, harbors, bayous, rivers, canals and lakes. The largest of these seiches was about 2 meters in crest-to-trough height; the smallest was measured in centimeters.

The remote stimulation of large seiches by a fault rupture thousands of kilometers away requires an earthquake of historic proportions. But this does not mean that seiches in general are uncommon. Many different mechanisms can trigger seiches; the seismic motion of the crust is just one of them. Thanks to scientists such as the late William L. Donn of the Lamont-Doherty Geological Observatory and City College of

**Figure 1. Seiches are free (unforced) standing waves that develop primarily in closed or semiclosed bodies of water. Although rare, large seiches and surges can be dangerous because they shift water levels through ranges that can exceed 3 meters. Their mode of onset makes these phenomena especially deserving of respect (and may explain a worldwide shortage of seiche photographs). Normally, the water surface**

New York, the stimulation of seiches by remote earthquakes is now well documented and explained. However, many other seiche-triggering mechanisms are less well understood, even though the seiches they create are more common than the remotely triggered ones studied by Donn.

### The Half-Wave Oscillator

Seiches are resonance phenomena made up of free (unforced) standing waves that oscillate according to the configuration of the basins in which they occur. We can find the natural period of standing waves in a given water body using a simple equation known as Merian's formula. Merian's formula predicts that the largest and simplest long-axis standing-wave oscillation in a rectangular, enclosed water body of constant depth will have a natural period equal to twice the length of the body divided by the square root of the product of gravity's acceleration and the water depth. This formula allows us to see at a glance that with other factors held constant, greater water-body lengths yield longer periods, whereas greater water depths yield shorter periods.

Whether Merian's formula is applied to fluids held in man-made enclosures or to the water bodies of nature, the results will almost always be useful, but they will be inaccurate to the extent that the bodies involved are not truly rectangular or of constant depth. These period predictions apply only to the largest standing-wave oscillation possible. This is known as the fundamental, or first, mode. Merian's formula yields first-mode standing-wave periods of 2 to 3 seconds for bathtubs, 8 to 12 seconds for swimming pools, and a few minutes to several hours for the water bodies of nature. (It is important to note that the natural periods predicted in this way apply to whole-body standing-wave motion; they do not apply to the much smaller surface waves that can be produced by winds, falling objects or the movements of vessels.)

First-mode calculations are based on the assumption that when an enclosed water body undergoes standing-wave oscillations, its tilted surface forms exactly half of a complete standing wave, with the low side in the trough and the high side forming a crest. A body that oscillates in this manner is known as a half-wave oscillator.

### Sloshing and Resonance

Coffee cups and bathtubs provide excellent opportunities to create the seiche analogue known as sloshing and experience natural periods and resonance first hand. Anyone who has carried a cup of coffee across a room has personally experienced sloshing. And anyone who has sat in a partially filled bathtub and rocked back and forth has experienced sloshing and the buildup of large standing waves when the tub's resonant frequency is discovered.

With a suitable board used as a paddle, you can kneel beside a partially filled bathtub and generate your own seiches. There are two basic ways man-made or natural seiches can be formed: by creating horizontal currents at a node (a point where horizontal currents reach their maximum speeds and vertical motion is nil), or by moving the surface up and down at an antinode (a point where vertical currents reach their maximum speeds and horizontal motion is nil).

Apply either method once, remove the board and use a stopwatch to find the tub's natural sloshing period—the time interval between any two successive antinode crests. The same procedure allows you to witness damping, the gradual dying of oscillations as gravity flattens the surface and friction converts the kinetic energy of coherent sloshing first into turbulence, then into heat.

By applying either method repeatedly at the tub's natural sloshing period, you can demonstrate both resonance and the amplification that occurs at resonance. When you fine-tune your movements to synchronize them with the natural rocking movements of the tub, you achieve resonance. Amplification occurs when a second, reflected crest rises to an only slightly damped position and receives a perfectly timed thrust from its driving mechanism, which lifts it above its first-crest height. The process continues as long as the driving mechanism exists. Although the buildup of amplitude at resonance can be spectacular, it cannot create infinitely large standing waves, primarily because of friction losses.

### Seiche-Driving Mechanisms

Having considered some basic seiche concepts, we can now look at the mechanisms that generate seiches in nature. For fully shoreline-enclosed water bodies exposed to the atmos-

**changes its slope too gradually to attract much attention. Thus, in seiche- or surge-prone waters, a wading fisherman who has heard a radio-dispatched warning and is ready to sprint from an oncoming wall of water may find himself and his catch high and dry at one moment and then, not many minutes later, may find his feet lifting off the bottom and his waders filling up.**

of the bay and a single antinode at the shoreline opposite the mouth. A second antinode is not necessary as long as forcing currents exist at the mouth of the bay. Thus, the length of the bay is occupied in the fundamental mode by only one-fourth of the seiche wavelength, and the bay becomes a quarter-wave oscillator. Since Merian's formula for the fundamental seiche period is based on a half-wave oscillator, twice the length of a bay must be used to calculate its fundamental period. The fundamental period of a bay is, therefore, twice that of a fully enclosed water body of the same length.

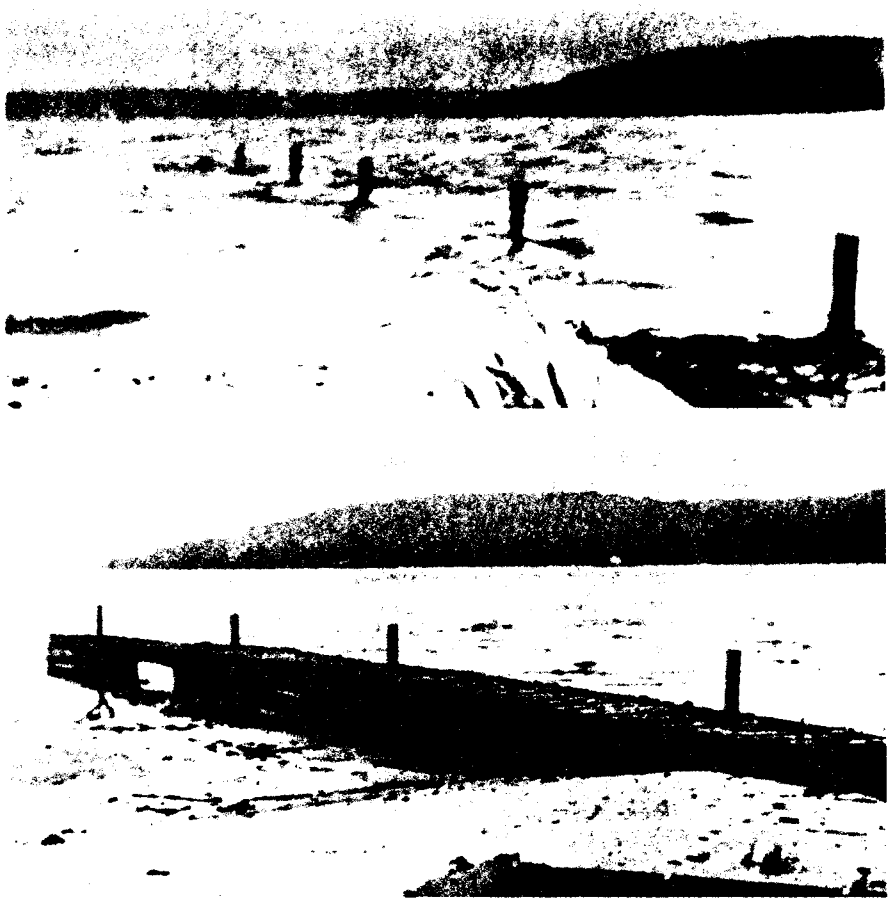


Figure 2. Seiche in action at Grand Island off Munising, Michigan, on August 19, 1921. The upper photograph shows a pier and a portion of the Lake Superior shoreline at 11:30 in the morning. The lower photograph shows the same scene just 20 minutes later.

phere, the most common seiche-driving mechanisms include fluctuations in air pressure, changes of wind speed or direction and local solid-earth events such as earthquakes, volcanic eruptions and landslides. For the same water bodies, other more rare seiche-generating mechanisms may come into play. These include uneven and transient distributions of raindrop-impact forces, sudden additions or removals of water to or from localized portions of water bodies, and uneven and transient distributions of electrical attraction between water surfaces and passing thunderclouds. Two or more driving mechanisms may also act in concert to generate seiches.

It is natural to think of all shoreline-enclosed water bodies as being seiche-prone. If a perturbing force deforms the surface of such a body and moves on, the deformed surface is out of equilibrium and movement results. Because of shoreline enclosure, the released mound of water must reflect off the solid boundaries in the form of standing waves. In nature, reflection of this kind is most efficient at the hardest, smoothest and most vertical boundaries. For these reasons, shoreline-enclosed water bodies with steep rocky sides are often the most seiche-prone.

These ideas are worthwhile, but they can be limiting if driving mechanisms are overlooked. Open-ended water bodies that appear to be less seiche-prone are exposed to more driving mechanisms than their shoreline-enclosed counterparts. A bay or harbor that is connected to offshore waters can be perturbed to form seiches by any of the mechanisms listed previously as well as by several mechanisms that can move in from offshore through the bay or harbor entrance. The same is true for shelf waters that are directly exposed to the open sea.

Most significantly, seiches can be triggered by horizontal motion at the open end of a water body such as a bay. In this scenario, the first-mode seiche has a single node at the mouth

### Energy from Deeper Waters

Several mechanisms can transfer energy from deeper waters toward land in ways that will generate seiches in shelf waters, bays or harbors. The best known are tsunamis (large waves generated by ocean-floor earthquakes) and long-period waves driven by a phenomenon known as surf beat.

When tsunami waves approach land and enter shelf waters, bays and harbors, they can trigger seiches that continue to oscillate for hours or even days after the tsunami itself is over. If a group of tsunami waves has a period that differs substantially from that of the basin it enters, the seiche it triggers will oscillate at the natural basin period with amplitudes that depend on the amplitude of the incoming waves. This type of seiche can be less than spectacular. If, in contrast, an incoming tsunami wave group has a period (typically from 10 to 20 minutes) that approximates the natural period of the basin it enters, a resonant seiche occurs. The result can be dangerous and destructive.

Even though their periods are too short to stimulate seiches directly, ordinary wind-driven surface waves can feed energy into seiches through a period-shifting mechanism. Two wave trains approaching the same beach with similar but slightly different periods drift in and out of phase when they interact, alternately reinforcing and diminishing each other. This creates the familiar shift between larger and smaller waves known as surf beat. The period of the surf beat (usually 1 to 3 minutes) is defined as the time interval between the centers of two adjacent larger-wave sets.

Wave-breaking at the shoreline filters out the shorter swell periods and allows the longer surf-beat period to remain, moving water shoreward in a series of long-period pulses. Some of the energy in these pulses is lost to turbulence and heat, but some is reflected back out to sea. In effect, the shoreline becomes a source of long, low waves that oscillate at periods long enough to trigger seiches in some nearshore waters.

### Surges as Related Phenomena

Although they are often called seiches, especially in the Great Lakes region, surges differ from seiches in that they do not "feel" the sizes of the basins they move in. Surges occur regularly in the southern basin of Lake Michigan, especially in May through September. Most of these are modest in size, causing water level changes that range from 30 centimeters to approximately a meter, but exceptional and dangerous examples have been recorded. Such was the case on June 26, 1954, when a major surge invaded the Chicago lakefront, sweeping eight fishermen to their deaths.

These unexpected surges are caused by intense squall lines that move rapidly toward the southeast. A squall's unique air-pressure jump and anomalous wind field combine to deform the lake surface into a long, flat wave of relatively insignificant amplitude. On shoaling (being forced into smaller and smaller zones of containment as shallower depths are encountered), a wave of this kind radically increases in amplitude, causing water levels to rise unexpectedly. Historically, the most dangerous surges observed at Chicago result when a wave of the kind described strikes the southeastern shore of Lake Michigan as an incident wave, then bounces back toward Chicago as a reflected wave.

Based on theoretical work performed by George W. Platzman and his colleagues at the University of Chicago, a strategy has been developed for accurately predicting surges that are driven by squall lines. This strategy relies on computer simulations that consider how a squall line's pressure rise, direction of travel, width and speed of forward progress drive surges that interact with the bottom and shoreline configurations. The resulting predictions show not only which storm systems will cause surges but also where surges will be most important, how big they will be and when they will arrive at the Chicago lakefront. The Chicago office of the U.S. Weather Bureau adopted Platzman's approach in 1960 to predict major surge events and issue public warnings. The approach has been successfully used since that time by the Weather Bureau and its successor, the National Weather Service. The effort has probably saved scores of lives in the Chicago area alone.

### Unexplained Driving Mechanisms

The driving mechanisms for some motions that appear to be seiches remain incompletely explained. An especially dangerous and interesting class of events takes the form of large, tsunami-like waves that enter coastal waters unexpectedly in fair weather and without any known triggering mechanism in evidence. Accounts of such events have come from Japan, Ireland, the Azores, the Baltic Sea, the Western Mediterranean and elsewhere. Reports refer to them as meteorological tsunamis in Japan, death waves in Ireland, *inchas* or *lavadiads* in the Azores and *seebärs* in the Baltic.

These peculiar events have the periods and forms of seiches and they are often significant. Noteworthy events move water levels 1 to 2 meters vertically, and exceptional events force vertical motions that approach 3 meters.

Progress toward understanding these events was probably slowed in the past by the widely held belief that seiches were characteristic only of

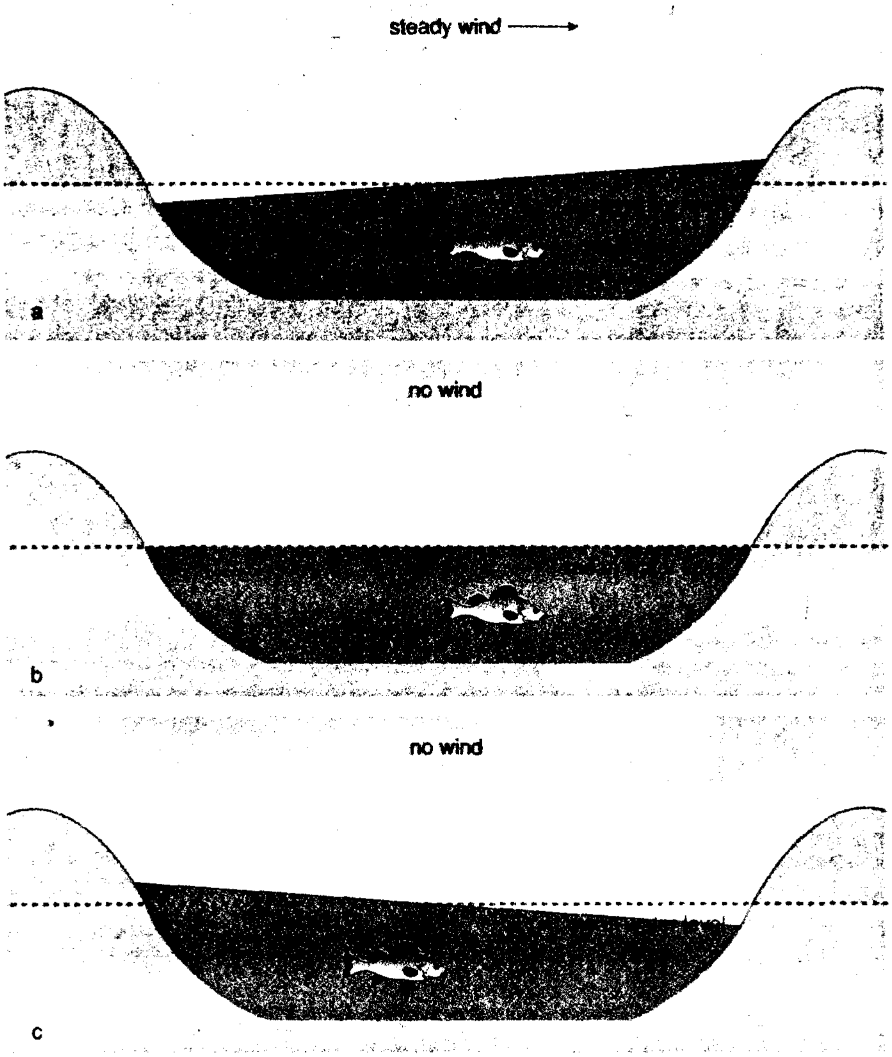



Figure 3. Wind-relaxation seiche is triggered when a steady wind creates a tilted water surface and then changes direction or subsides. During a steady wind, frictional and pressure couplings between moving air and the water surface create ordinary wind-driven waves as well as a tilt that has the dimensions of half of a complete wave *(a)*. This tilt is referred to as a wind set. When the wind subsides, the system is out of equilibrium, and the downward acceleration of gravity acts to level the water surface *(b)*. Because inertia is high and friction low throughout most of the water volume, the water surface overshoots its level position and takes on the oppositely directed tilt *(c)*. As it did before, gravity acts to level the new tilt and the sequence continues for hours or even days with vertical displacements gradually subsiding as part of the damping process. The effect is muted if the wind decreases gradually.

shoreline-enclosed or at least partially shoreline-enclosed basins. It is now evident, however, that standing-wave oscillations can take place in continental shelf waters with or without a significant degree of shoreline enclosure.

In general, all that is needed to create a damped coastal seiche is a triggering mechanism that moves the shelf floor, tilts the sea surface or creates horizontal currents at a potential node. A damped coastal seiche may become an amplified coastal seiche if the triggering mechanism repeats itself with a period at or near the natural period. When Merian's formula for a bay is adapted to fit a coastal seiche by replacing bay length with shelf width, the agreement between computed and observed periods is not perfect, but it is good enough to instruct us that coastal seiche oscillations involve the shelf waters and not much more or less.

An improved understanding of coastal seiches has opened the door for a number of scientists who have concentrated on revealing previously unknown seiche driving mechanisms. But before their results can be fully appreciated, an understanding is needed of internal seiches and internal waves in general.

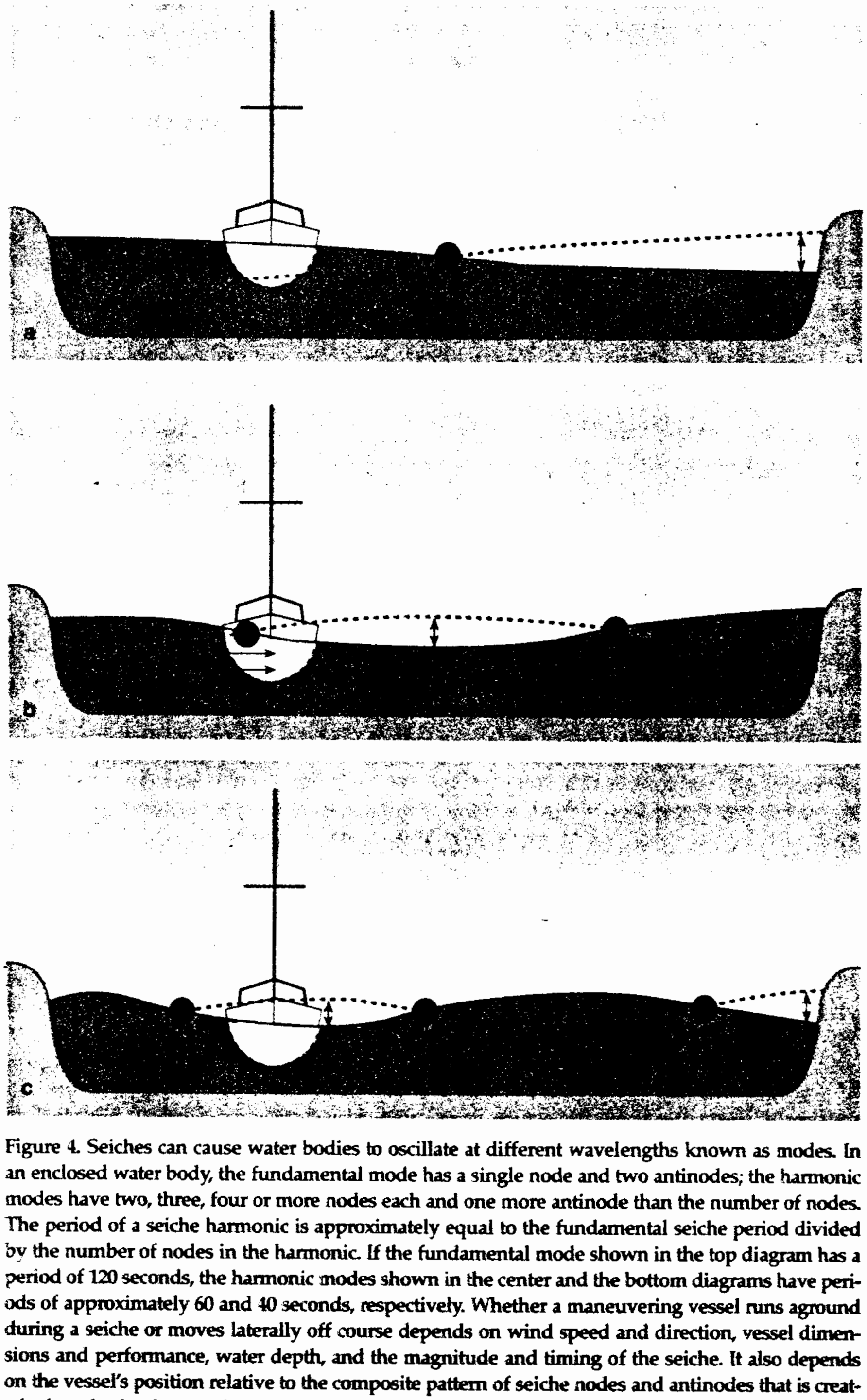



Figure 4. Seiches can cause water bodies to oscillate at different wavelengths known as modes. In an enclosed water body, the fundamental mode has a single node and two antinodes; the harmonic modes have two, three, four or more nodes each and one more antinode than the number of nodes. The period of a seiche harmonic is approximately equal to the fundamental seiche period divided by the number of nodes in the harmonic. If the fundamental mode shown in the top diagram has a period of 120 seconds, the harmonic modes shown in the center and the bottom diagrams have periods of approximately 60 and 40 seconds, respectively. Whether a maneuvering vessel runs aground during a seiche or moves laterally off course depends on wind speed and direction, vessel dimensions and performance, water depth, and the magnitude and timing of the seiche. It also depends on the vessel's position relative to the composite pattern of seiche nodes and antinodes that is created when the fundamental mode is superimposed on its harmonics.

### Internal Seiches and Internal Waves

Consider a stratified, two-layered lake (for example, warm in the upper layer and cool in the lower layer) over which a steady wind has been blowing for several hours. Ordinary wind-driven surface waves roughen the surface, of course, but in addition, the wind piles water against the windward shoreline where a small portion of its volume causes the lake surface to rise. A much larger portion of the wind-piled water volume causes the thermocline (the boundary between the two layers) to fall. Thus, while the surface tilts upward at the windward end, the thermocline tilts in the opposite direction and at a much steeper angle. The steeper angle of the thermocline is caused by the lower density contrast across the thermocline relative to that across the air-water interface.

Now we can consider what happens when the wind across our stratified lake subsides. The opposite tilts are both out of equilibrium because the driving force that established them has been removed. Subsurface flow systems are established in directions that tend to level both interfaces. But because inertia is large and friction is minimal in this fluid system, both interfaces overshoot their equilibrium positions, flop toward tilt directions opposite to those originally established by the wind, and then proceed to tilt back and forth in a series of damped oscillations.

These oscillations take the form of free standing waves, and their wind-failure driving mechanism is known as wind relaxation. Thus, the end result is a double wind-relaxation seiche. Although the surface and internal seiches start out 180 degrees out of phase, this relationship cannot persist. Because of the smaller density contrast across the thermocline compared to that across the surface, the internal seiche oscillates with a longer period than the surface seiche, and the two seiches continually drift in and out of phase.

Internal seiches make up a subset of the more general category of internal waves. Internal waves are single-medium, density-interface waves that can be either forced or free and either progressive or standing.

When internal waves move along a density interface within the atmosphere that overlies a water body, they can drive surface seiches in the water body. To do this, the embedded air waves must oscillate at or near a natural seiche period of the water body. Preliminary evidence suggests that atmospheric internal waves may be driving mysterious, large surface seiches in the Western Mediterranean by actively pumping air-pressure fluctuations onto the sea surface.

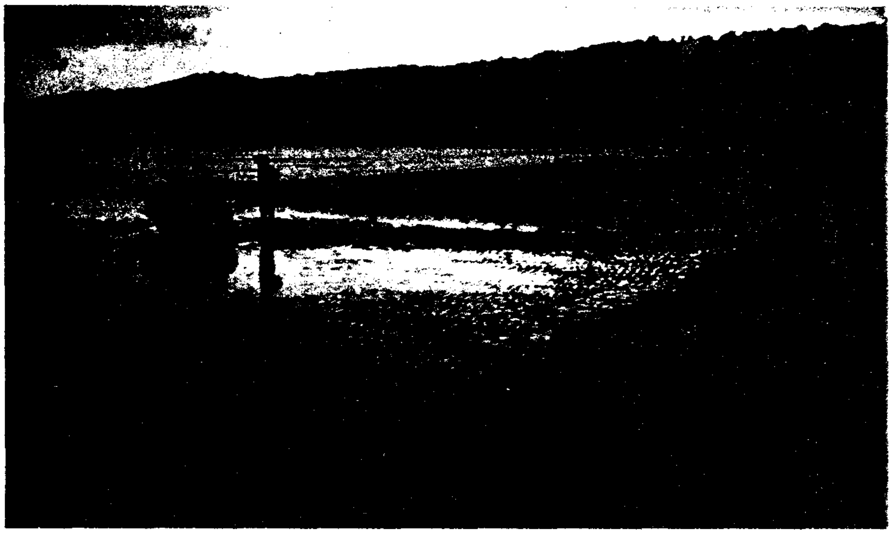


Figure 5. Air-pressure changes continually force water levels to change. Small pressure-driven water-level changes go unnoticed in virtually all exposed waters; larger changes go unnoticed along oceanic shorelines where they are masked by the astronomical tides. This photograph documents what relatively few people have witnessed: a major change in water level that was driven by a moving air-pressure jump. It was taken in August 1988 at Grand Island in Lake Superior off Munising, Michigan, where astronomical tides are small. The calm water surface also suggests that winds were too weak to account for the changes observed. (Photograph courtesy of Sandy Davis.)

### Revelations from Nature

Considering non-seiche internal waves in the water column has led to some encouraging progress in our understanding of a special class of coastal seiches that have stubbornly resisted attempts to attribute them to atmospheric phenomena or to earthquakes. A breakthrough in this direction came in 1982 when a group of scientists supported by the Puerto Rico Sea Grant Program concluded that internal waves generated by tidal currents were creating coastal seiches at Magueyes Island.

Led by Graham S. Giese, currently at the Woods Hole Oceanographic Institution, the scientists of the Puerto Rico study found that off Magueyes Island, the maximum number of coastal seiche oscillations per month was recorded in late summer and early autumn, when thermal stratification of the water column is at its annual maximum. They also found that seiche activity reached a maximum approximately seven days after a new or a full moon. This led them to speculate that the coastal seiches they had observed were excited by tide-generated internal waves similar to those that had been observed by other investigators working in the Andaman and Sulu Seas. These were not ordinary periodic internal waves that arrive as quasi-symmetrical, paired pulses of up-and-down thermocline deformation. Instead, they were negative internal solitons, a peculiar class of waves formed from pulses of purely downward thermocline deformation.

In the Andaman and Sulu Seas, internal solitary waves were found to be generated when tide-driven flows of stratified water move over sea-floor discontinuities such as shallow sills. The work of John R. Apel and his colleagues has shown that a strong ebb tide moving south over a shallow sill at the southern boundary of the Sulu Sea causes the formation, on the south side of the sill, of a zone of rough water at the surface and a depression in the thermocline. When the tide changes, the broad depression in the thermocline moves northward over the sill, maintaining its velocity relative to the tide. As the depression propagates northward, internal undulations within the depression rapidly evolve into solitons with amplitudes of up to 90 meters.

In Puerto Rico, Giese and his colleagues found that the seven-day interval between either the new or the full moon and maximum seiche activity could be accounted for by internal soliton formation near the southeastern margin of the Caribbean Sea, where tidal effects are at a maximum for the region. In this location, the time lag between either the new or the full moon and a maximum tide is about two days, and soliton travel times from this region to Puerto Rico would be about five days.

Later, Giese and Ruth B. Hollander found evidence that the tidal current-soliton mechanism is also driving coastal seiches off Puerto Princesa on Palawan Island in the Philippines. This result strengthened the idea that the newly observed mechanism might be generating at least some of the unexplained seiches that have been recorded at widely scattered places around the world. It also brought into focus the need to go beyond correlations into the realm of cause and effect.

Progress had already been made (by Apel and others, for example) toward understanding how tidal currents generate internal solitons. This meant that significant progress toward understanding the entire mechanism could be made if they could learn how internal solitons might transfer energy to coastal seiches.

### Theoretical Approaches

At this point, Giese was joined by David C. Chapman, a theoretician at the Woods Hole Oceanographic Institution. Chapman began to study both the internal soliton-to-seiche mechanism and the comparable periodic internal wave-to-seiche mechanism. He developed a mathematical model of the processes involved, believing that it might both establish the credibility of these mechanisms and eventually lead to the ability to predict tide-generated seiches.

To make his model correspond to what had been observed, Chapman placed the model thermocline below the shelf break and in contact with the continental slope. With the thermocline in this position, any internal waves generated by the model could not directly enter the model's coastal waters. Instead, they would move toward land and impinge on the continental slope. Could energy from internal waves moving along an interface well below the coastal waters somehow transfer their energy into the coastal waters in ways that would generate seiches? Evidently so, because the model runs show that both periodic and solitary internal waves could indeed excite coastal seiches. In the model, currents moving onshore

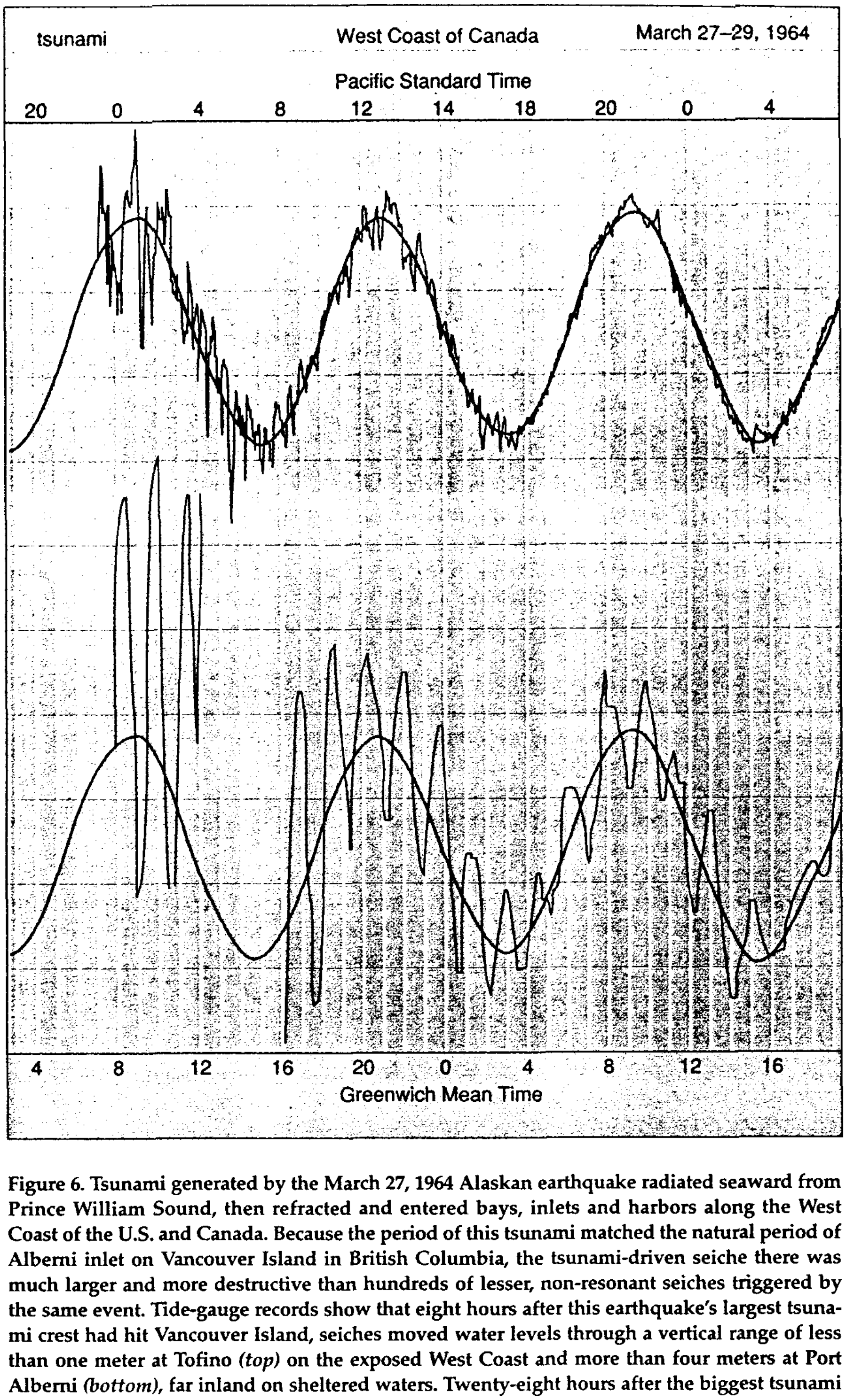



**Figure 6. Tsunami generated by the March 27, 1964 Alaskan earthquake radiated seaward from Prince William Sound, then refracted and entered bays, inlets and harbors along the West Coast of the U.S. and Canada. Because the period of this tsunami matched the natural period of Alberni inlet on Vancouver Island in British Columbia, the tsunami-driven seiche there was much larger and more destructive than hundreds of lesser, non-resonant seiches triggered by the same event. Tide-gauge records show that eight hours after this earthquake's largest tsunami crest had hit Vancouver Island, seiches moved water levels through a vertical range of less than one meter at Tofino *(top)* on the exposed West Coast and more than four meters at Port Alberni *(bottom)*, far inland on sheltered waters. Twenty-eight hours after the biggest tsunami crest arrived, the seiche height ranges were down to 27 centimeters at Tofino, but were still more than two meters at Port Alberni. Green lines indicate the underlying, predicted tides for each location, and the black lines are the measured water levels. (Adapted from the Marine Sciences Directorate, Department of the Environment, Ottawa, Canada.)**

over an incoming internal wave trough push water over the continental shelf, providing the horizontal movement needed to generate a coastal seiche.

At this stage, the model results make the newly described phenomenon believable, and they identify a mechanism—the horizontal motion of water in the upper layer—that can make it work. The results also indicate that periodic and solitary internal waves may behave similarly in driving seiches. However, because the geometry of the model is relatively simple, its results cannot spell out the details of how the mechanism might act in nature. For example, the vertical continental slope used by Chapman reflects internal waves back out to sea. The more complicated interaction between internal waves and a sloped approach to the shelf has not yet been theoretically resolved.

When either periodic or solitary internal waves move toward a real continental shelf, they may be expected to break on the inclined continental slope. Whether internal waves of either kind can break on the slope in ways that generate seiches is both a reasonable question to ask and one that is still open to debate. It is reasonable to hypothesize that as a periodic internal wave breaks on the slope, it could send an internal "swash," or wave of translation, riding over the shelf break to become the horizontal node current that triggers a coastal seiche.

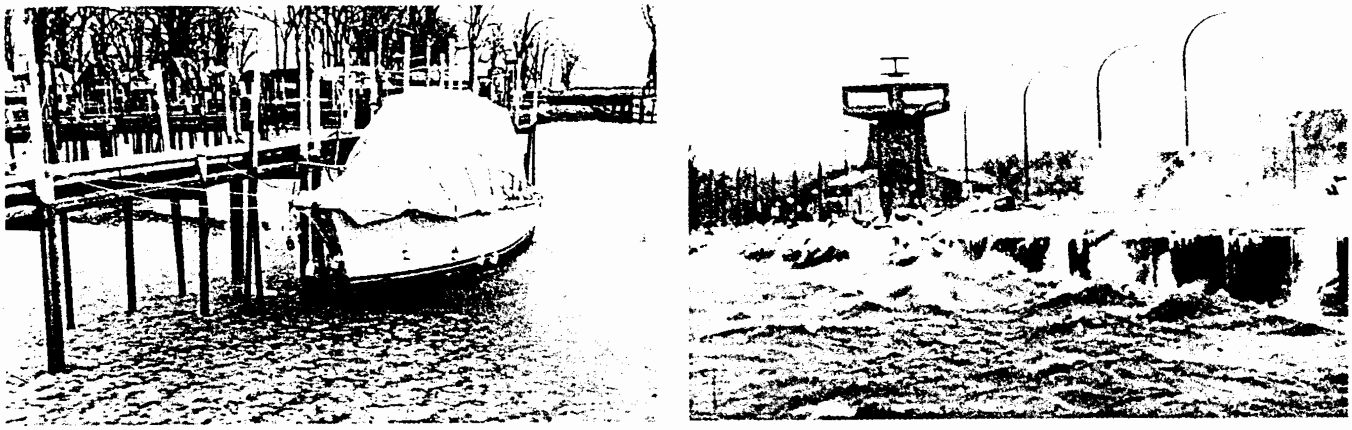
Does a similar process occur when a negative internal soliton breaks on the continental slope? Supporting evidence for such upward and landward transports of water was provided in 1991 by Jesús Pineda, then a doctoral student at the Scripps Institution of Oceanography. Pineda showed that when tide-driven, internal solitary waves interact with a shoaling sea floor, they transport subsurface cold water to the shore, along with the drifting larvae that play key roles in the structuring of benthic communities.

Working together on Palawan Island in the Philippines, Chapman and Giese have gathered evidence that Sulu Sea internal solitary waves generate internal swashes. In addition, their colleague Karl Helfrich, a physical modeler at the Woods Hole Oceanographic Institution, has demonstrated that internal solitary waves generate both internal swashes and coastal seiches in a stratified tank with a simulated continental slope and shelf. At the present time, it is clear that the swash phenomenon can trigger coastal seiches, but there is no clear evidence that it is required. In fact, the theoretical work suggests that horizontal currents traveling above internal waves can cause coastal seiches without the swash.

### Seiche Effects

We are just beginning to grasp the effects of seiches on human activity and on physical and biological processes in the water column.

Our insights into the impacts of seiches on human activities are probably best with regard to harbor design and vessel maneuvering and mooring. We know, for



(U.S. Army Corps of Engineers)

Figure 7. Wind set is most impressive in long, relatively shallow lakes that are oriented in a direction preferred by local windstorms. Lake Erie provides a classic example: Strong southwest winds often pile up water at the northeastern end of the lake, dropping water levels at Toledo, Ohio, and raising them at Buffalo, New York. A docked pleasure boat sits on the bottom at the Toledo Yacht Club during such a wind-set event *(left)*. High water with damaging waves strike the Buffalo Marina during a similar event *(right)*.

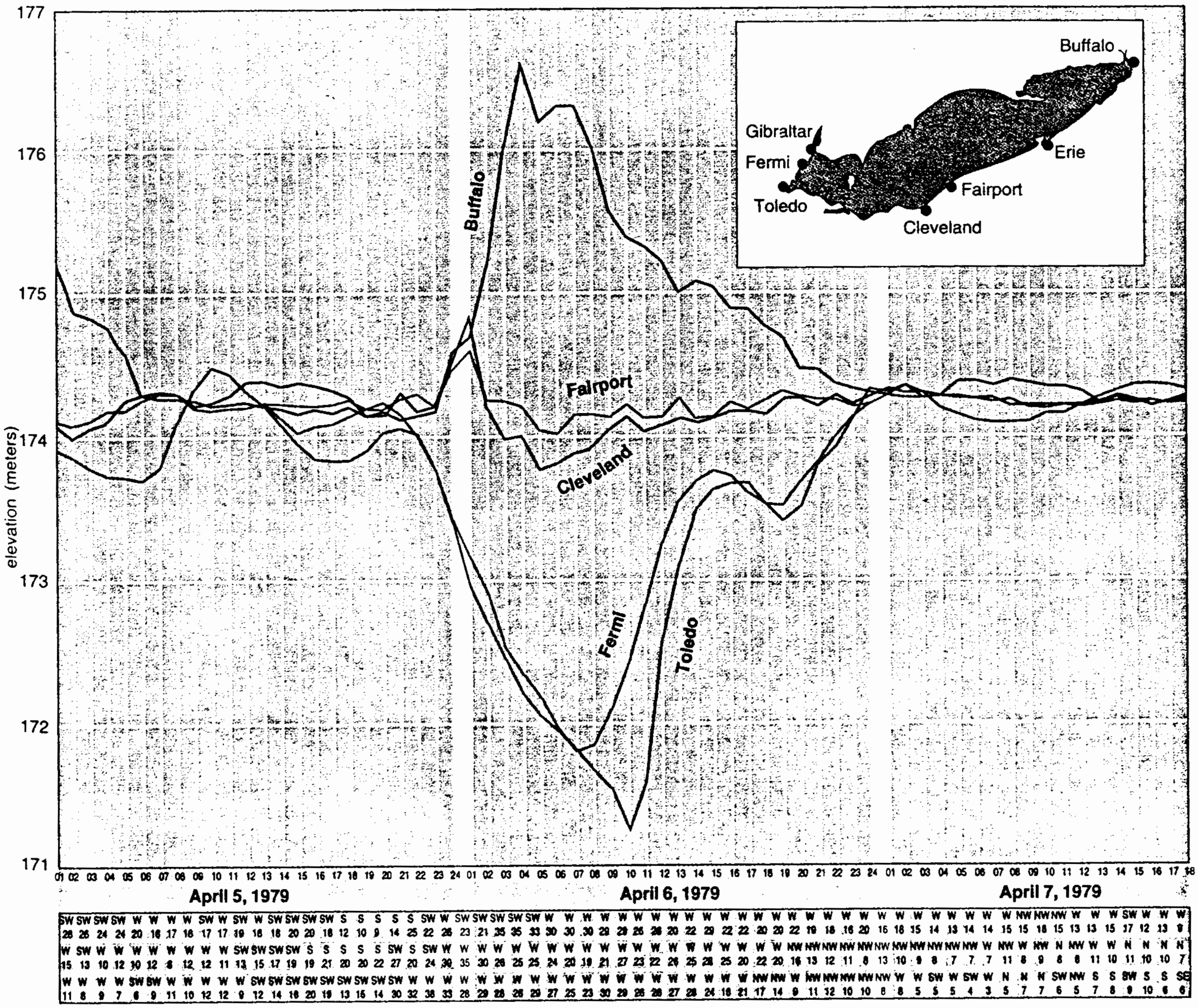



Figure 8. Graph shows water levels at selected Lake Erie locations during the great storm of April 6, 1979. When a storm of this magnitude suddenly fails to maintain the water surface tilt it has created, the result is a major wind-relaxation seiche. When wind relaxation is followed by strong winds that spring up from the same direction after an interval that corresponds to the basin's natural period of oscillation (about 14 hours for Lake Erie), a spectacular and dangerous amplified seiche may result. The largest seiches of this kind in Lake Erie can cause significant variations in river flow downstream at Niagara Falls. (Adapted from NOAA/NOS/OMA Great Lakes Acquisition Unit.)

example, that seiches can be among the most important factors that determine the usefulness of some harbors. Seiches have moved maneuvering vessels out of their channels and aground, and their oscillatory surge currents have caused moored vessels to snap their mooring lines and to slam into each other.

The navies of the world have interests in seiches that go beyond problems connected with harbors. As navies evolve, they become more sophisticated and increasingly dependent on a flow of environmental information. Furthermore, with the end of the Cold War, naval plan-

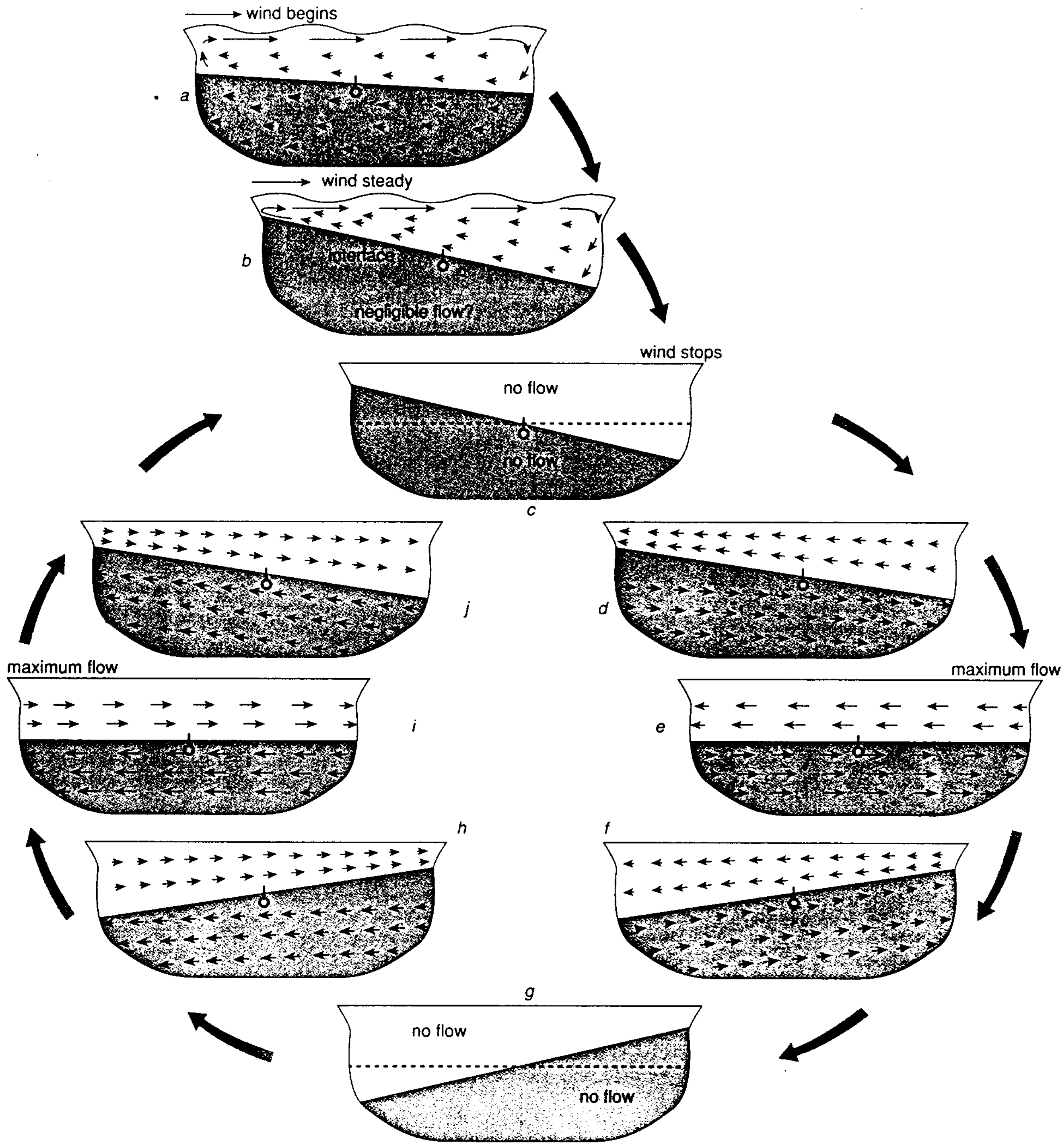



**Figure 9. Double wind-relaxation seiche is triggered when a steady wind acts on a stratified, two-layered lake and then subsides. The amplitude of the surface seiche is small compared to the internal seiche, and only the internal seiche is shown here. Initially *(a)*, a rising wind establishes circulations that preferentially move water to the windward end. After a period of steady wind, a temporary state of equilibrium is reached *(b)*. The surface tilts upward at the windward end, but only slightly because the strong density contrast between air and water effectively aids the downward acceleration of gravity in its efforts to level the air-water interface. The subsurface density interface is the thermocline—the interval (in this case very narrow) over which water temperature decreases rapidly with increasing depth. The thermocline tilt is in the opposite direction of the surface tilt, and it is much steeper because of the relatively weak density contrast between the upper and lower layers. When the wind stops *(c)*, the system is out of equilibrium, gravity acts to level the two tilted surfaces, and a double relaxation seiche *(d–j)* is triggered. The small arrows indicate approximate flow directions and speeds (longer arrows represent stronger current speeds) for a hypothetical lake neglecting internal friction. The symbol ♁ identifies the nodal section where the strongest horizontal currents and weakest vertical movements are observed. (Adapted from C.H. Mortimer, *Philosophical Transactions B* 236:335–404.)**

ners have dramatically shifted their interests away from the vast, deep ocean to focus on the shallower waters near land. This shift in emphasis places a special premium on information about phenomena such as seiches, which depend on interactions with land in shallow water.

My own work with seiches has largely been concerned with informing U.S. Navy planners of the extent to which seiches could affect various kinds of naval operations. This information is generally site-specific and includes predictions of a maximum range of vertical water-level change, the predominant periods of oscillation and the time needed to go from the first important standing wave arrival to a damped state of operational insignificance. The information is usually derived from a combination of historical data and theoretical considerations.

It is also possible to predict how a seiche could alter or control a particular kind of naval operation. For example, a seiche can resuspend sediments in ways that alter the visibility of divers working near the bottom. In addition, seiche-driven resuspension, transport and deposition of sediments could bury bottom mines, equipment, tools or other objects left resting on the bottom. Pressure-sensitive mines designed to activate when they sense the underwater pressure signal of a passing vessel could be detonated prematurely by the pressure fluctuations that underlie the standing waves of a seiche. Also, a vessel maneuvering through a cleared zone within a minefield could be moved into uncleared areas by the strong, oscillatory currents of an unexpected seiche.

Seiches pose a double threat to naval operations such as amphibious landings. The power of unexpected water-body oscillations could kill personnel and damage or destroy equipment. In addition, illumination of near-shore waters by seiche-excited bioluminescent organisms could temporarily reveal the locations of people, vessels and equipment when the cover of darkness is expected.

It is clear that seiches have a significant effect on physical and biological processes in the Great Lakes of the U.S. and Canada. This is true partly because of the highly reflective, shoreline-enclosed character of these massive lakes; the frequent presence of impressive seiche-driving mechanisms; and the observed results, which include spectacular surface and internal seiches. It is also true because tides are small and tidal currents are weak in the Great Lakes, making seiches and seiche-driven currents more important there than they are in the tide-dominated shallow waters that border much of the ocean. In the most seiche-prone bays of the Great Lakes, seiches may be the most important single physical process that determines how pollutants are distributed or how nutrients are lifted from below into the sunlit surface

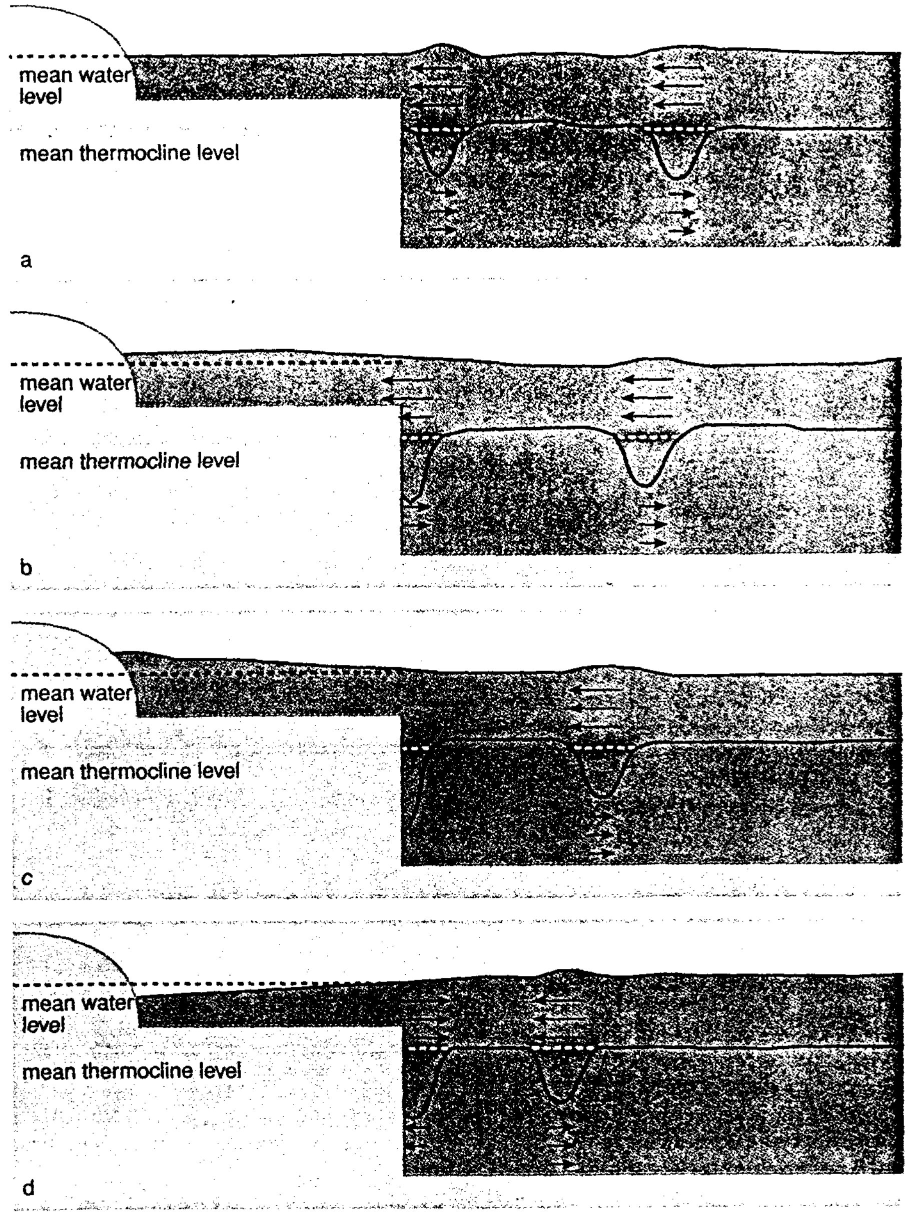



**Figure 10. Internal solitons form a unique class of internal waves that propagate along thermoclines alone or in packets of up to 10 arranged in the order of their size, with the largest pulses in the lead of the propagating packet. An internal soliton is negative, as shown, if, as is most often the case, the depth of the thermocline is less than the depth interval from the thermocline to the bottom. Each negative internal soliton moves in association with a gently domed surface soliton, a surface rip zone of turbulent water, and a current system that allows the complete soliton structure to move forward (from right to left) with its geometry intact. Negative internal solitons can extend downward to hundreds of meters below the thermoclines they traverse, and their strongest horizontal currents attain speeds that can exceed two meters per second. Onshore currents that overlie each landward-moving negative internal soliton pulse can trigger seiches in coastal waters that are exposed to a stratified region of the open sea. In the simplified geometry of the model, a soliton trough approaches shallow water with its associated current system intact *(a)*. (Vertical currents are omitted from the drawing for simplicity.) As the trough reflects off the model's vertical land boundary, the current in the upper layer is directed toward shore *(b)*, diminishes as it encounters an adverse pressure gradient *(c)* and is then directed offshore *(d)*, initiating seiche oscillations. If additional solitons move landward and repeat the process at the same time that the shoreline is already rising as part of a free oscillation, resonance and amplification can result.**

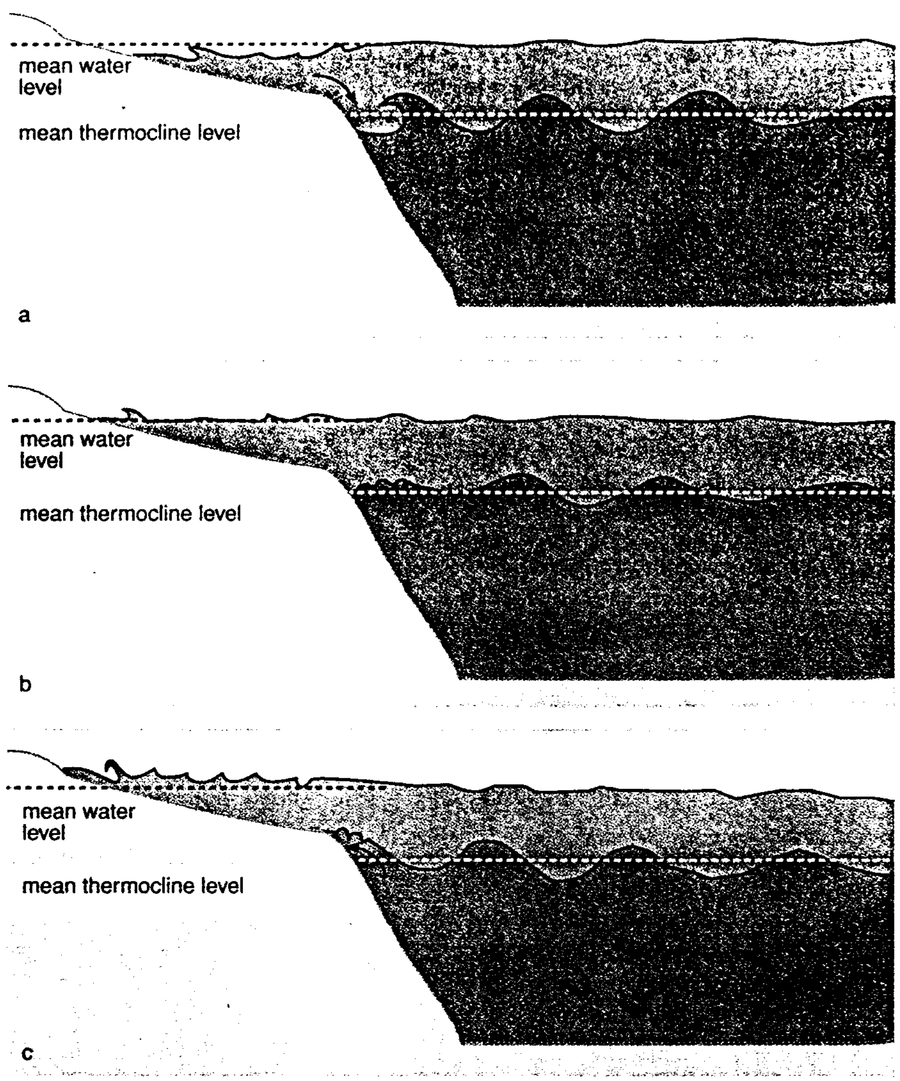



**Figure 11. In a more realistic geometry than was shown in Figure 10, periodic or solitary internal waves may generate seiches by a slop-over process. This presumes that a large internal wave breaking on a continental slope can send a bolus of below-interface water over the shelf break and onto the continental shelf, where it provides the nodal current that initiates a coastal seiche. In the periodic example shown, the internal wave crest nearest land curls over, pulling its density interface down so upper ocean waters fill the hollow thus created, causing the shoreline to retreat *(a)*. The same internal wave crest then collapses into a mass of turbulent eddies, and the shoreline passes through an approximately level position *(b)*. Momentum and mass from the broken internal wave slop over the shelf break and slide toward land as a wave of translation that completes the initiation of a coastal seiche *(c)*.**

waters where living tissue is formed by photosynthesis.

Beyond these recognitions, our progress has been limited. A hint that we might have been overlooking the importance of seiches in oceanic regions with low tidal ranges comes from water-clarity data collected by Kendall L. Carder of the University of South Florida in 1978 during a routine winter survey in the eastern Gulf of Mexico. Carder's time series of water clarity measurements, taken both near the sea floor and in midwaters, showed that boluses of turbid water alternated with clear water in a highly periodic manner. Using spectral analysis techniques, Carder found that pulses of increased turbidity were spaced apart in time by 10.6, 20 to 22.7 and slightly over 40 hours. Knowing that the fundamental seiche mode for the Gulf of Mexico is 21.1 hours, Carder hypothesized that seiches were resuspending sediments at intervals that corresponded to multiples of half the fundamental seiche period (with two erosional events in each complete seiche cycle).

This idea has provided new insights into the biological economy of water bodies through the work of Steven J. Eisenreich and Joel E. Baker, environmental chemists at the University of Minnesota. Eisenreich and Baker have focused their attention on the behavior of trace organic pollutants (PCBs, DDT and others) in large lakes and on the benthic nepheloid layer, a discrete zone of highly turbid water that overlies the floor of many water bodies around the world.

With support from the NOAA National Undersea Research Program at the University of Connecticut and the Minnesota Sea Grant College, these scientists used a submersible to explore first Lakes Huron and Superior, then Lake Michigan. Since their first dive to the floor of Lake Superior in 1985, Eisenreich and Baker have been excited about the abundance and variety of life in the sediments there. More important, they have perceived some significant links between these organisms, seiches, the benthic nepheloid layer and the general distribution of nutrients and pollutants in the lake.

In their dives, Eisenreich and Baker have made direct observations of sediment-dwelling organisms efficiently stirring materials free and moving them upward into the benthic nepheloid layer. Some of these scientists' earlier, indirect measurements in the same waters showed that seiches are highly effective mechanisms for maintaining benthic nepheloid layers or building their dimensions by resuspending previously deposited sediments. In western Lake Superior near Duluth, during stratified, summer conditions, near-bottom currents driven by a single seiche event were strong enough to build the benthic nepheloid layer's vertical thickness from 5 to 15 meters.

The materials moved upward into the nepheloid layer contain nutrients that would otherwise be locked within the sediments below. They also contain long-forgotten pollutants. Considering that both are actually present in highly mobile, concentrated forms within the benthic nepheloid layer, these scientists were immediately struck by the profound implications of what they had discovered: A seiche-controlled nepheloid layer can be an important source of raw materials for the water column, like an engine that helps to drive the system, rather than merely serving as a repository of particles that settle out when seiche energy subsides.

And what about the timing of the soliton-seiche mechanism? Could it trigger biological events? In the Puerto Ri-

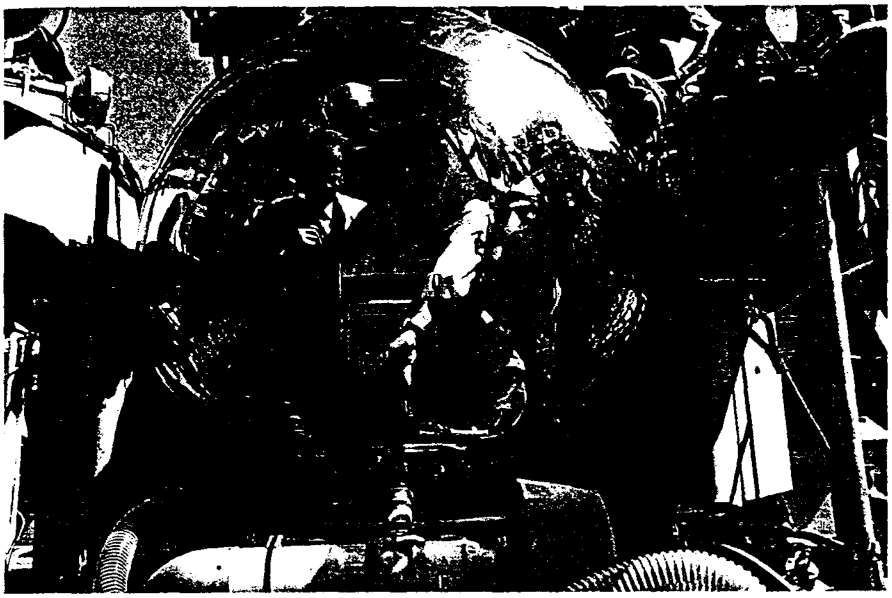


**Figure 12. University of Minnesota environmental chemists Steven J. Eisenreich *(left)* and Joel E. Baker *(right)* have used *Johnson Sea Link II* in a series of dives to the floor of Lake Superior. They have found that animal-mobilized, seiche-built benthic nepheloid layers are an important water-column source of nutrients and pollutants that, without these processes, would be permanently locked in sediments below.**

can waters where it was first discovered, the mechanism appears most likely to create seiches in summer and autumn a few days after either the full or the new moon. Research performed by Alina M. Szmant of the University of Miami has established that Caribbean reef corals, brittle stars and polychaete worms of the kinds that live in Puerto Rican waters are most likely to spawn in summer and autumn a few days after either the full or the new moon. Could the correspondence in timing between seiche events and spawning suggest that some reef organisms have evolved to spawn when they can depend on seiche events to stir up nutrients at a when sunlight is already abundant? At this point, we do know that the timing of spawning in general is triggered by many more mechanisms than seiches alone. We just do not know if particular species of organisms depend on seiches for the timing of their spawning.

## Implications for the Future

So what remains to be done in the effort to understand the newly recognized seiche driving mechanisms? First, more refined internal wave-seiche models can be developed through more extensive theoretical work with more realistic bottom topography. Furthermore, our grasp of the internal wave-seiche mechanism's worldwide significance can be accelerated using more extensive experimental work focused on regions that lie in the paths of tide-generated internal waves. Finally, we can accelerate implementing the results of seiche research by further examining the optical, biological, geological and chemical implications of seiches.

In the context of human activity, most work to date has concentrated on trying to predict the dimensions and consequences of seiches—the aftereffects. With few exceptions, the research community has largely bypassed the problem of trying to *predict* seiches. In the future, prediction might be enhanced through further research in several specific areas. The pioneering work of George Platzman might be extended to predict seiches driven by atmospheric phenomena at many key seiche-prone regions around the world. The present tsunami warning systems might be extended to yield more comprehensive predictions of seiches triggered by earthquake-driven tsunamis. Finally, the "instrumented ocean" concept might eventually make it possible to monitor the oceanic water column well enough to predict coastal seiches driven by phenomena such as periodic internal waves and internal solitons.

## Acknowledgments

*Marshall D. Earle, Steven D. Haeger and Gordon E. Wilkes reviewed an early version of this article and contributed many helpful suggestions that were used in revising it. All of the scientists mentioned in this article reviewed either the entire manuscript or the portions that apply to their work. Their contributions were indispensable in creating the final result.*

## Bibliography

Apel, J. R., J. R. Holbrook, A. K. Liu and J. J. Tsai. 1985. The Sulu Sea internal soliton experiment. *Journal of Physical Oceanography* 15:1625–1651.

Baker, J. E., and S. J. Eisenreich. 1989. PCBs and PAHs as tracers of particulate dynamics in large lakes. *Journal of Great Lakes Research* 15(1):84–103.

Baker, J. E., S. J. Eisenreich, T. C. Johnson and B.M. Halfman. 1985. Chlorinated hydrocarbon cycling in the benthic nepheloid layer of Lake Superior. *Environmental Science & Technology* 19(9):854–861.

Chapman, D. C., and G. S. Giese. 1990. A model for the generation of coastal seiches by deep-sea internal waves. *Journal of Physical Oceanography* 20:1459–1467.

Donn, W. L. 1964. Alaskan earthquake of 27 March 1964: remote seiche stimulation. *Science* 145:261–262.

Giese, G. S., and D. C. Chapman. 1993. Coastal seiches. *Oceanus* 36:38–46.

Giese, G. S., D. C. Chapman, P. G. Black and J. A. Fornshell. 1990. Causation of large-amplitude coastal seiches on the Caribbean coast of Puerto Rico. *Journal of Physical Oceanography* 20:1449–1458.

Giese, G. S., and R. B. Hollander. 1987. The relationship between coastal seiches at Palawan Island and tide-generated internal waves in the Sulu Sea. *Journal of Geophysical Research* 92:5151–5156.

Giese, G. S., R. B. Hollander, J. E. Fancher and B. S. Giese. 1982. Evidence of coastal seiche excitation by tide-generated internal solitary waves. *Geophysical Research Letters* 9:1305–1308.

Gomis, D., S. Monserrat and J. Tintoré. 1993. Pressure-forced seiches of large amplitude in inlets of the Balearic Islands. *Journal of Geophysical Research* 98:14,437–14,445.

Herman, R. 1992. Solitary waves. *American Scientist* 80:350–361.

Mortimer, C. H. 1952. Water movements in lakes during summer stratification; evidence from the distribution of temperature in Windermere. *Philosophical Transactions of the Royal Society of London Series B* 236:355–404.

O'Keefe, S., F. B. Kelso II and C. E. Mundy Jr. 1992. ...From the sea: Preparing the naval service for the 21st century. *U.S. Naval Institute Proceedings* 118:93–96.

Okihiro, M., R. T. Guza and R. J. Seymour. 1993. Excitation of seiche observed in a small harbor. *Journal of Geophysical Research* 98:18,201–18,211.

Pineda, J. 1991. Predictable upwelling and the shoreward transport of planktonic larvae by internal tidal bores. *Science* 253:548–551.

Pineda, J. 1994. Internal tidal bores in the nearshore: Warm-water fronts, seaward gravity currents and the onshore transport of neustonic larvae. *Journal of Marine Research* 52(3):427–458.

Platzman, G. W. 1958. A numerical computation of the surge of 26 June 1954 on Lake Michigan. *Geophysica* 6:407–438.

Rabinovich, A. B., and A. S. Levyant. 1992. Influence of seiche oscillations on the formation of the long-wave spectrum near the coast of the southern Kuriles. *Oceanology* 32:17–23.