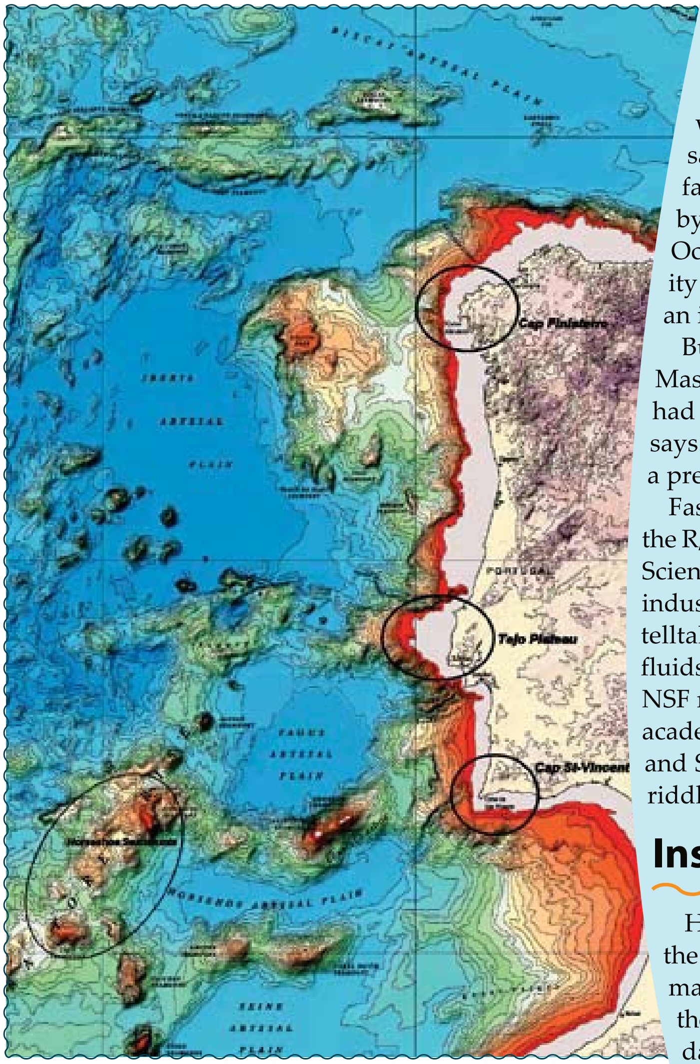
Internal Waves Beneath the Sea

Lucas Laursen

Seismologist W. Steven Holbrook and oceanographer Raymond Schmitt might be forgiven for talking past each other aboard a research cruise. Oceanographers normally drop probes overboard, measuring the ocean's temperature, chemistry and motion. To seismologists, however, the ocean is in the way of their measurements: They typically tune their microphones to detect echoes from below the seafloor in search of clues about Earth's structure. But over the past five years, Holbrook and Schmitt have learned to listen to each other — and to apply seismic techniques to hear hints of the ocean's structure.

Meddies — warm, salty eddies of Mediterranean water — are often generated by instabilities in the water flowing from Gibraltar, as seen in this bathymetric map.



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Together the pair is championing the emerging field of seismic oceanography. Seismic oceanographers listen to echoes reverberating off natural boundaries within bodies of water. Those boundaries exist because sound travels at different speeds in different parts of the ocean, due to the changes in temperature, pressure and density that occur when currents of water slide past each other at different speeds. By recording the echoes of explosions from an air gun, scientists can create a detailed visual chart (called a seismic profile) of those water boundaries, mapping where the speed of sound changes: Oceanographers call these internal changes in temperature, pressure and density the "fine structure" of the ocean. Much of that fine structure is still poorly understood, but the pair hopes that by visualizing the wispy meters-long "fingers" that occur where bodies of water mix, they can help oceanographers decipher how heat moves around the ocean through currents, a critical step necessary for understanding the planet's climate.

The odd couple

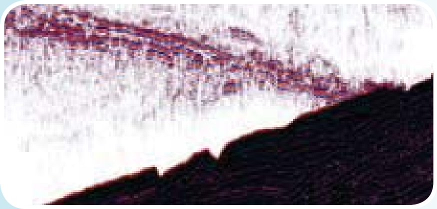
Holbrook, of the University of Wyoming in Laramie, first published on the oceanographic potential of seismic reflection profiling in Science in 2003. "When I first wrote that paper, I thought, 'This is going to set the physical oceanography world on its ear. Nobody's ever seen the ocean like this,'" he says. But only a few oceanographers have shown interest so far. Instead, Holbrook says, the majority respond to his images by saying, "'That's fascinating, but can you give me numbers?'" Oceanographers are used to measuring the temperature and salinity of water directly, so they don't necessarily know what to do with an image that shows them only where those properties change.

But Schmitt, of the Woods Hole Oceanographic Institution in Massachusetts, grasped the possibilities right away. "I immediately had ideas on what he was seeing and found it quite intriguing," he says. "I had worked years earlier on the fine structure … so it was a pretty natural collaboration."

Fast-forward five years to April 2008: The odd couple is aboard the R/V Marcus G. Langseth, a seismic-capable ship that the National Science Foundation bought from Western Oil. The hydrocarbon industry has used seismic reflection profiling for decades to find telltale density changes below the seafloor. Such changes reveal fluids such as hydrocarbons hidden between sedimentary layers. NSF recently refurbished the ship, making it the most sophisticated academic seismic profiling rig in the United States. Now, Holbrook and Schmitt are setting out to discover what sort of oceanographic riddles seismic oceanography can solve.

Inside the sea

Holbrook and Schmitt are at sea off Costa Rica in the Caribbean; the water is smooth, but only at the surface. It is the Langseth's maiden voyage, but the researchers are already growing excited by the ship's performance. From the ship, Holbrook posts preliminary data to his Web site. The ship's air guns have a "source signature



A seismic profile of an internal wave breaking against the coast of Norway in 2004.

far superior to anything previously available in the academic community (anywhere in the world), and it appears ideally tuned for seismic oceanography work," he writes in an e-mail.

From the beginning, Holbrook envisioned measuring the internal waves within the ocean. Like waves at the surface, internal waves are caused by a combination of tides and surface winds. Tides and wind "put energy in at very long wavelengths, creating internal waves" that are kilometers long, Holbrook says. The interactions between those internal waves then create shorter waves that eventually break up into turbulence beneath the surface. It is at those turbulent boundaries that distinct but connected bodies of water — such as the Mediterranean and the Atlantic — exchange their heat, salt and even biologically important nutrients.

But oceanographers do not find it easy to measure how much energy and mixing internal waves contribute to the entire ocean's mixing budget, which is a tally of how much energy different bodies of water exchange by physical contact. Mixing mechanisms such as internal waves are the way in which the ocean's energy changes its form from heat to kinetic, or its location from one current to another. "The problem is that the internal wave field is a fairly complex thing," says Chris Garrett of the University of Washington in Seattle. "We don't have a good handle on the flows of energy going into the internal wave field. We have a better understanding of where energy goes out."

Traditional oceanographic techniques to measure ocean mixing rely on anchored underwater buoys or costly expendable probes. Another method uses sound at a much higher frequency, but it is limited to depths of a few hundred meters and is "not wildly informative by itself," Garrett says. None of these techniques permits rapid measurements across large areas — but seismic reflection profiling can do just that.

Because internal waves possess different properties from their surroundings, their sharp boundaries are comparatively easy to detect in the seismic profiles. Holbrook and Ilker Fer of the University of Bergen in Norway demonstrated the concept off the coast of Norway in late 2003. There, they recorded profiles that matched oceanographers' predictions for how internal waves should look. In Costa Rica, Holbrook and Schmitt hope to use these profiles to obtain higher-resolution quantitative measurements that they can use to understand the turbulence generated by internal waves.

The waves below the Langseth off Costa Rica are playing nice. The seismic profiles and expendable current and temperature probes agree on where the turbulence exists, Schmitt says. The internal waves are smooth for several kilometers at a stretch, but both the oceanographic probes and the seismic profiles found jagged sections up to a kilometer long in the same places.

"I like to call it internal whitecapping," Schmitt says, because the underwater waves mimic how their surface counterparts look on windy days. Subsurface turbulence, which appears as a frothy region in the seismic profiles, is set off primarily by tides and currents moving across seafloor topography, with a small contribution from surface winds. The combination of the Langseth's top-of-the-line air guns and the good conditions in the water means the pair has high hopes of extracting measurements of the energy carried and dissipated by the internal waves.

The R/V Marcus G. Langseth at sea.

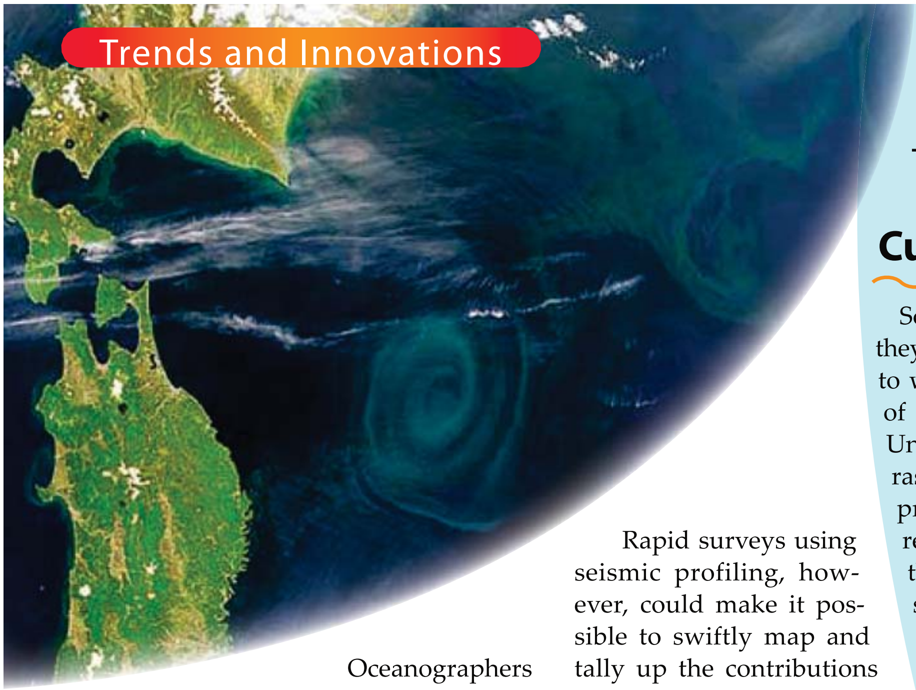
Once they get a good grasp of how the larger-scale internal waves work, they want to go into the finer details of smaller-scale turbulence. This, Holbrook says, "is the process that really ties directly to mixing." The pair thinks most heat exchange takes place via small-scale mixing. And quantifying this mixing will be critical for any serious model of how heat moves around the ocean.

What goes down comes up?

Ocean mixing is still too poorly understood to be calculated or predicted in global climate change models. But it's a key player: "The ocean is sort of the flywheel of the climate system," storing and moderating exchanges of heat energy, Garrett says. He repeats the conventional wisdom that a single cubic meter of seawater contains about the same amount of heat energy as the entire column of air above it. Yet climate modelers "can't be bothered to get the ocean right," Schmitt says. An exact model of mixing would require so much computing power that "we can't model [it] in a computer and it'll be hundreds of years before we can."

Garrett agrees: "Numerical models cannot calculate things on the scale of mixing and we can't imagine a time in the future when they could." But he also emphasizes that creating accurate climate models will require more than just mimicking how the ocean mixes today. Even if it were possible to build a computer model faithful to current mixing without understanding what makes it work, he says, "when the climate state changes we won't really have any ability to predict [mixing] in the future … so we have to get the physics of it correct."

Bottom: Lamont-Doherty Earth Observatory; top: Steven Holbrook and Ilker Fer

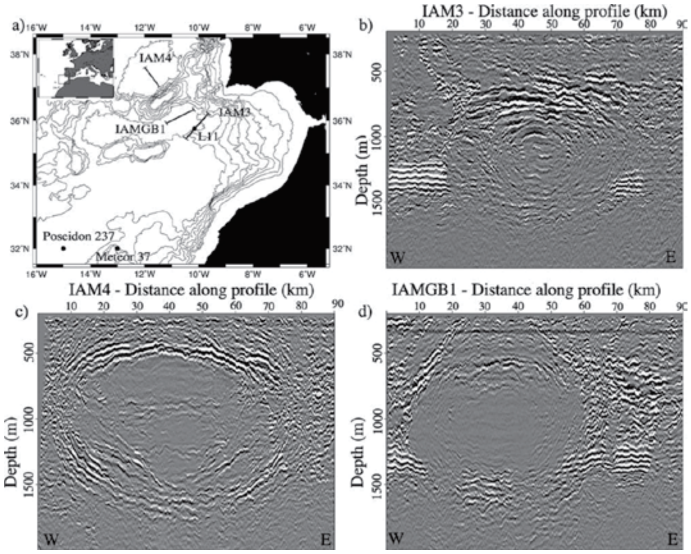


Eddies seen from space.

Oceanographers interested in mixing also face an observational problem: What's going down isn't coming up. "The sinking of water at the poles has been known for over a hundred years," Garrett says. "But how and where it rises is a much more difficult issue." The ocean is our planet's biggest heat engine, constantly carrying solar and tidal energy via currents and releasing it in unknown ways. If oceanographers can understand how water mixes, they will be most of the way toward understanding how it moves heat — as it does, for instance, with the Gulf Stream that heats Western and Northern Europe, making it agriculturally fertile. Laborious and time-consuming oceanographic measurements have only found some of the necessary upwelling water, so "people look for hot spots of mixing" to figure out where upwelling may be occurring, Fer says.

Rapid surveys using seismic profiling, however, could make it possible to swiftly map and tally up the contributions of underwater structures like internal waves and mixing hotspots. It is like a dietitian determining how much energy each type of food contained just from listening to a person's stomach. But the surveys' value isn't just limited to counting calories. "Having the cross-sectional images where you can say, 'Oh there's the shape of these things,'" could be useful in unexpected ways, Holbrook says. "I think we're going to find things that nobody has predicted."

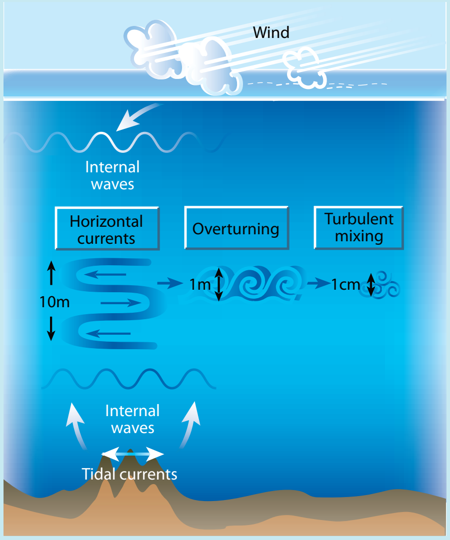
Holbrook hopes to also offer numbers that oceanographers can immediately understand like the temperature and concentration of salt in seawater. "For me, the grail is to give them a number ... that they care about." The data from the Langseth voyage, he says, promise to do that.



This year, a Spanish research team identified these three meddies in seismic data collected five years ago.

Culture clash

Some oceanographers are not entirely clear on how they'll use seismic profile data. "We are so unaccustomed to working with it that we still have to develop ideas of what to do with it," says Gerd Krahmann of the University of Kiel in Germany. In a way, it's an embarrassment of riches: The traditional method of dropping probes from ships yields extremely precise vertical resolution down to centimeters or less. But because the probes are expensive and the ships must move so slowly to drop them, typical transects are spaced kilometers apart. A ship like the Langseth can trail multiple parallel sound recording arrays, however, mapping a wide swath of the ocean with resolution better than 10 meters in both the vertical and the horizontal directions.



Seismic oceanography aims to figure out the internal waves and the mixing going on well below the ocean surface. Waves produced at the sea surface and seafloor propagate into the ocean interior, generating mixing processes that affect ocean circulation, heat transport and nutrient distribution.

Yet the models oceanographers currently use simply don't have a place for that detailed horizontal information. So when seismologists and oceanographers discuss the uses of seismic profiling, they don't always have the same goals. "If you asked a physical oceanographer what we've learned about the water column and a seismologist what we've learned, you [would] get slightly different answers," Holbrook says. "And that's because the viewpoints of the two fields are very different!"

Bottom: Berta Biescas and Valenti Sallares; middle: Christopher Garrett, reprinted by permission from Macmillan Publishers Ltd: Nature, copyright 2003; top: NASA

Measuring meddies

The Langseth's April voyage took longer than expected, so Holbrook and Schmitt were unable to attend the European Geophysical Union's meeting in Vienna, where they had hoped to meet with their European counterparts. There, a network of European Union-funded researchers discussed the results of a 2007 seismic profiling cruise near the Strait of Gibraltar.

Like Holbrook, European researchers are anxious to demonstrate that it is possible to extract quantitative results from their images. Some are focusing on another watery denizen of the deep: meddies. Meddies are discs of warm, salty water that spin away from the underwater current emerging from the Mediterranean through the Strait of Gibraltar. They can stretch a hundred kilometers across, with thicknesses of hundreds of meters, and persist in the Atlantic for months or years. At their edges, they slowly interact with the colder water of the Atlantic and eventually dissipate their large heat and salt payloads, so they too are a target for oceanographers.

Anything that can move so much heat from one area to another is bound to have a significant impact on the local climate and currents. And changes in salinity affect what marine life can survive in a given body of water. So researchers want to know as much as they can about how the Mediterranean and Atlantic exchange heat and salt. A June 2008 paper in Geophysical Research Letters reported the successful detection of several meddies using seismic reflection profiling. Lead author Berta Biescas of the Marine Technology Unit of the Spanish National Research Council in Barcelona, Spain, and colleagues plan to apply the technique to simultaneous seismic and traditional oceanographic data from the 2007 research cruise.

"Steve and I must confess to a little professional jealousy of their opportunities," wrote Schmitt from the Langseth in April. The European project, like the American effort, is intended to produce the first generation of quantitative seismic oceanography studies. By simultaneously taking seismic reflection profiles and traditional oceanographic measurements, the project's results could serve as a standard for future calibration of seismic data, says the project's director, Richard Hobbs of Durham University in the United Kingdom. "The Mediterranean causes layers of warm water to slide beneath colder Atlantic layers," Schmitt notes, so "they should see some very strong signals."

Researchers on both sides of the Atlantic hope that by producing a reliable conversion between oceanographic techniques and seismic reflection profiling, they can tap into another resource: decades of seismic profiles recorded by the oil exploration industry. These historical data are not perfectly adapted to the needs of oceanographers, as exploration firms were interested in the areas below the seafloor and not the intervening water column. Still, the data have the advantage of a long historical baseline and do not require expensive new voyages.

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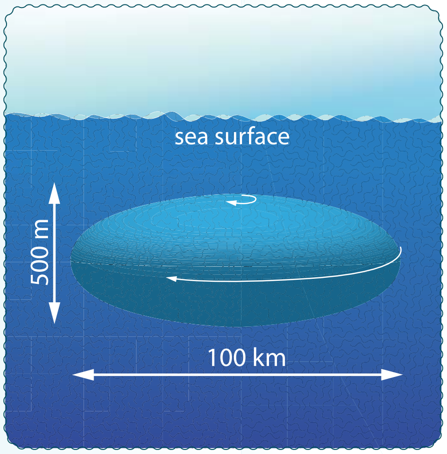
– Steven Holbrook, University of Wyoming



Meddies float beneath the sea surface and usually rotate clockwise.

Brenna S. Tobler, AGI, from illustration by Mark Prater and Thomas Rossby

Access to those data does require the cooperation of the exploration companies, points out Rob Hardy, a geophysicist at the University College Dublin in Ireland: "Generally they're quite good at providing data … but you have to find the right budget code."

An answer or a question?

Months after their sea voyage, Holbrook and Schmitt are still analyzing the data from the Langseth. They haven't submitted their results for publication yet, but Holbrook says he is finalizing a method that he is convinced "works to quantify turbulence dissipation. We can take a seismic image and from that return a number." The preliminary numbers, he says, are in line with oceanographer's estimates for the missing upwelling water.

Still, Holbrook returns to the theme that seismic oceanography is not just about the numbers: "Even at a qualitative level you can look at [seismic profiles] and see where things are churned up and mixed." The images, Holbrook hopes, could spark an unexpected insight for an oceanographer mulling over a mixing model, or serve as an entry point for geoscientists familiar with seismic profiles and curious about the mysteries of the sea.

Perhaps most intriguing, Holbrook says, is that seismic profiling has the potential to answer other questions oceanographers can't yet answer or don't even yet know to ask. "There are still features in the original images," Holbrook says, "that nobody's explained to me."

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