Seismic Oceanography Allows a New View of the Ocean

In their efforts to better understand the oceans' small-scale processes and the mixing of coastal and deep ocean water, NRL scientists and their international colleagues are developing seismic oceanography (SO), a new technique for observing oceanic water masses. The technique was discovered serendipitously when researchers realized that seismic systems that were designed to image sub-seafloor geologic structures were also providing images of oceanic water layers.

SO, in using lower frequency sound waves than those used in acoustic oceanography, represents a new way of measuring the vertical temperature gradient throughout the water column, both vertically and laterally, and at orders of magnitude finer resolution than that offered by traditional methods. In their experiments in March 2009 in the Adriatic Sea, the researchers acquired data in the Adriatic littorals and combined seismic and oceanographic data, then used the relationship between oceanic temperature contrasts and acoustic reflectivity to generate a 5- to 10-m resolution temperature gradient. If optimal field parameters are developed, and signal processing techniques are refined, SO can be incorporated as a practical standard research or operational oceanographic tool.

Seismic Oceanography — A New View of the Ocean

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NRL scientists are collaborating with international colleagues in developing a new way of observing water masses in the ocean: seismic oceanography. Using low-frequency seismic systems designed to image sub-seafloor geologic structures, thermohaline contrasts between water masses can be mapped, characterized, and quantified. Seismic oceanography uses the relationship between oceanic temperature contrasts and acoustic reflectivity to generate a quantitative measure of vertical temperature gradient throughout the water column at vertical and lateral resolution of 5 to 10 meters, several orders of magnitude finer than traditional methods. Such resolution opens up a new window on small-scale processes and mixing of the coastal and deep ocean. In 2009, we executed an ambitious field effort in the Adriatic Sea (ADRIASEISMIC-09) to acquire seismic data together with state-of-the-art oceanographic data as a way to compare the datasets and evaluate the limits and capabilities of seismic methods to characterize ocean processes. This was only the third such combined field effort ever performed, and the first in shallow water, thus adding to the useful development of this new approach. Incorporating seismic oceanography into standard oceanographic practice will require integrating field acquisition practices and developing new signal processing algorithms, with the potential benefit of gaining a new view of ocean structure.

A FAMILIAR TOOL FOR GEOPHYSICISTS USED IN A NEW WAY

Seismic oceanography (SO) is a new discipline born out of the accidental discovery that seismic systems designed to image sub-seafloor geologic structures, such as hydrocarbon traps, were also providing images of water layers in the ocean.[1,2] The ocean is very "thin" (general aspect ratio is 1000 to 1), but subtle differences in density of this thin "sheet of water" caused by temperature and salinity variations drive much of its motion and variability. Thus, much of observational oceanography is focused on accurately measuring horizontal changes in density that both drive ocean flows and come about as consequences of ocean flow dynamics.

Seismic reflections from ocean layers are about 1000 times weaker than reflections from sediment interfaces, and for decades geophysicists had been looking right through them without ever noticing them. The reflections require careful processing of high-quality seismic data to see and interpret, but can show subtle details in the water mass boundaries that occur on lateral scales of only a few meters (Fig. 1). Standard wire-line oceanography measurements, such as expendable bathythermograph (XBT) or conductivity-temperature-depth (CTD) casts, typically have measurement spacing of 1 to 10 kilometers; so the seismic oceanographic records with measurements every 5 to 10 meters, both horizontally and vertically, allow measurement of the ocean water masses at horizontal resolutions rarely seen. Because of the aspect ratio of the ocean, obtaining oceanographic measurements at similar resolutions both vertically and horizontally is very unusual, and so represents a new way of observing ocean phenomena.

WHAT CAUSES THE REFLECTIONS?

Seismic oceanography can be thought of as a type of acoustic oceanography (AO) but it differs in a very important way. The lower frequency sound waves used in SO, about 10 to 200 Hz, are coherently reflected (not refracted or incoherently scattered) directly by the

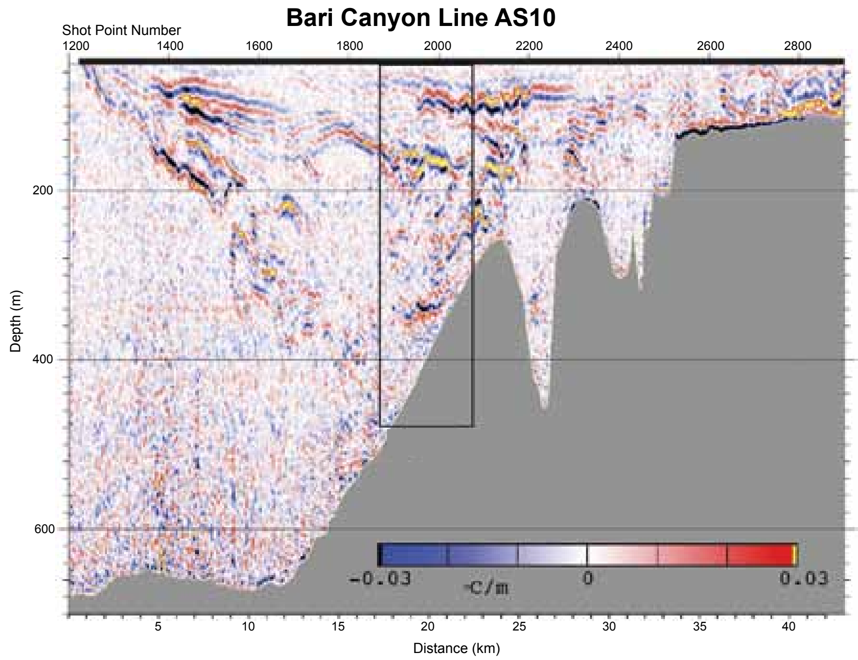

FIGURE 1
This calibrated seismic image is a cross section of the ocean in the Bari Canyon region of the Adriatic Sea, extending from deep water (left) up on to the continental shelf (right). The colors represent band-limited (smoothed) vertical temperature gradient (see Fig. 3). In this display, large, rapid temperature contrasts between water masses manifest as strong events. The boxed area was measured with a microstructure profiler (see Fig. 4) at a later time. Warmer colors indicate an upward warming (positive dT/dz), and cooler colors indicate an upward cooling (negative dT/dz).

thermohaline boundaries between water masses. These frequencies are affected by vertical changes on the scale of meters to tens of meters. Conversely, the sound waves commonly used in AO are at frequencies about 1000 times higher, 10 to 200 kHz, and are affected by features on the scale of microns to millimeters, such as suspended impurities or biota in the water column.[3] Although the scatterers seen in AO records (e.g., from acoustic Doppler current profilers, ADCPs) may be associated with physical boundaries, the AO records do not contain the information to quantify the magnitude of physical property contrasts between water mass boundaries as do SO records.

The acquisition geometry for SO is shown in Fig. 2. A ship moving at 4 to 6 knots tows a controlled sound source and a linear array of tens to thousands of hydrophones, both at a depth of a few meters. The sound source is typically an air gun, a device that explosively releases compressed air, creating a sound pulse in the ocean with a duration of 10 to 20 milliseconds. The sound pulse reflects off of near-horizontal interfaces such as sediment layers in the earth or vertical sound speed changes in the ocean, and is then recorded at the hydrophone array. Typically, the source is fired every 25 meters (about every 12 seconds). The hydrophone array contains 10 to 20 individual hydrophones that are summed to generate a single channel record, and may contain dozens to hundreds of channels, with each one providing an independent measurement of ocean reflectivity.

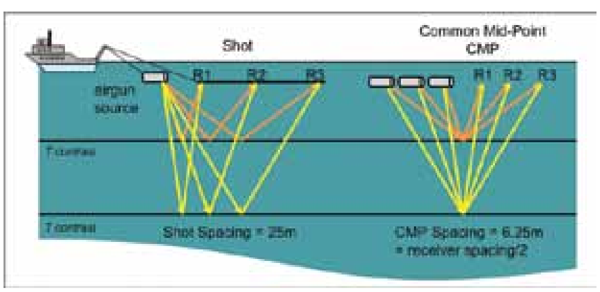

FIGURE 2
Seismic data are acquired while towing a source and a receiving array. Each channel in the array consists of 16 individual hydrophones whose signals are summed in real time to produce a single record of pressure vs time. Individual source-receiver records are rearranged post-acquisition into common midpoint (CMP) bins such that reflection points coincide. Time differences are removed (normal move-out correction) and CMP records are summed to enhance the signal-to-noise ratio.

The reflectivity is controlled by the contrast in acoustic impedance — the product of sound speed and density. In most places in the ocean, the sound speed has a much greater effect on the acoustic impedance than does the density. Thus a seismic reflection image is effectively an image of the sound-speed contrasts as a function of depth in the water column.[4,5] The reflections are strong or weak as the vertical temperature change is large and rapid or small and slow, respectively.

CONVERTING SEISMIC REFLECTIVITY TO TEMPERATURE CHANGE

Because acoustic impedance contrasts are dominated by temperature contrasts, there is a simple scaling factor that can be multiplied with the recorded reflectivity to yield a good approximation of the vertical temperature contrast. That is, the seismic image (a cross-section of impedance contrasts) is essentially a scaled, band-limited measurement of the vertical change in temperature, and can yield a cross-sectional image of the vertical change in temperature (Fig. 1). However, the band-limited nature of seismic data means that there will always be sidelobes that prevent a simple, exact, one-to-one correspondence between vertical temperature change and seismic reflectivity.

Figure 3 shows graphically how the temperature and reflectivity are related. The black curve is the observed water temperature from an XBT cast, and the red curve is its vertical derivative, i.e., the temperature gradient with water depth (dT/dz). We have displayed the curves in this figure using the oceanographic convention of viewing dT/dZ from the bottom up, opposite from the seismic reflectivity measurement made from the top down (source to target).

The salinity (not shown) is estimated from an empirical relationship derived from CTD profiles acquired in this same area within a day or two of the seismic records. Temperature and estimated salinity profiles are then used to calculate sound speed and density profiles, from which the acoustic impedance contrasts (green curve) can be calculated. The blue curve is the same estimated profile of impedance contrasts, but filtered to match the frequency band of the seismic data. The purple curve is a single column of data or trace of the observed seismic data (near shot point 2016 in Fig. 1). Finally, a group of several traces, displayed with color representing amplitude (i.e., a subset of Fig. 1) is shown on the far right side of Fig. 3. The similarity of the blue and purple curves is what allows the seismic data to be used as a quantitative estimate of the thermal gradient (dT/dz, red curve). Matching the amplitudes of these curves provides the scaling factor that converts the observed seismic reflectivity into an estimate of vertical temperature gradient seen in Fig. 1.

Although the correlation between expected and observed reflectivity (blue and purple curves in Fig. 3) is very good down to 200 meters water depth, the correlation degrades below 200 m for this particular example. Note also in Fig. 3 the poor lateral continuity of reflections in the plot of the seismic data (also seen in Fig. 1, around shot point 2000) at these depths. The poor correlation near shot point 2000 may be due to a significant difference in the lateral sampling range of the XBT and the seismic wave. While the XBT samples water over a tiny range (less than 1 cm in diameter), the reflection of a broadband spherical seismic wave is affected by the portion of the reflector within the first Fresnel zone (70 to 200 meters at the frequencies used).

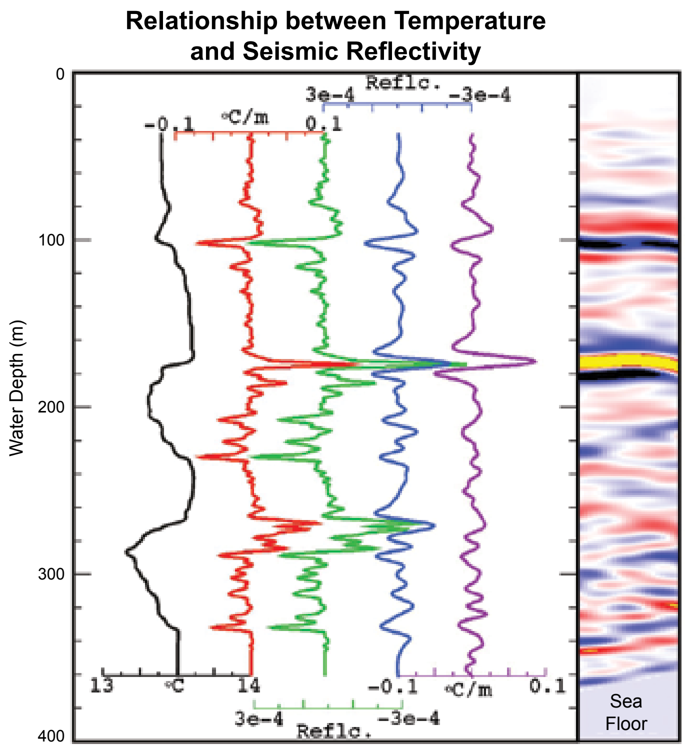

FIGURE 3
This display shows the steps relating the temperature profile with seismic reflectivity. (Black) Temperature measured from XBT 169 at shot point 2016 on line AS10 in the Bari Canyon, Adriatic Sea (see Fig. 1). (Red) Depth derivative of temperature from bottom, up. (Green) Impedance contrasts calculated from temperature and empirically derived salinity. (Blue) Impedance contrasts filtered to match the band of the seismic data. (Purple) Observed seismic data. (Far right) A series of seismic traces from the area in which the XBT was acquired. The large negative and positive events at 105 and 175 meters, respectively, correlate well to temperature contrasts in the XBT. Figure 1 shows these events to be laterally continuous. Conversely, the reflection events at about 320 meters depth are not as laterally continuous and do not correlate as well with predictions from the XBT.

A REAL-WORLD APPLICATION

By early 2009, seismic reflections from water mass boundaries had been reported and several analyses had been done using combined seismic and XBT data.[2,6,7] However, dedicated SO field programs with full seismic and oceanographic measurements had only been performed in the Kuroshio Extension in the western Pacific[8,9] and in the Mediterranean outflow area of the eastern Atlantic.[10] In both cases, the water column objectives were in blue water, greater than 200 meters deep.

In March 2009, NRL and several international collaborators conducted the ADRIASEISMIC-09 exercise to collect both seismic data and high-resolution oceanographic measurements in the Adriatic Sea, the first such exercise to include shallow (<200 m) water. During the exercise, we adopted SO techniques to follow the North Adriatic Dense Water (NAdDW) masses flowing southward from the coastal shelf into a deep basin. This is a complex process as the cold and fresh bottom shelf water suddenly encounters a warmer and saltier water resident in the deep basin, with which it mixes as it descends down the sill slope or through local canyon systems. The strong temperature contrasts that this generates, and the relatively fast action of the processes, were well suited for testing SO in shallow waters with the use of a "light" seismic system that could be deployed quickly, using only two small air guns. The project used two generator-injector air guns for the source, and a 1200-meter, 96-channel hydrophone array for the receiver.

However, since SO measurements alone are not sufficient to fully characterize such complex processes, the resulting seismic reflection data were combined with a series of more "classical" physical oceanography measurements, e.g., CTD profiles, ADCP measurements of ocean currents, 232 XBT casts simultaneous with SO sections, and — for the first time — microstructure (very high resolution) measurements acquired via a free-falling turbulence profiler (101 casts). The microstructure measurement provides data on a full suite of important oceanographic variables at vertical resolutions on the order of millimeters, providing a calibration for how SO-measured vertical temperature changes connect to small-scale dynamical factors.

Figure 4 shows one example of a microstructure data section (vertically averaged over 1 meter) taken along a portion of the same pathway of the SO section

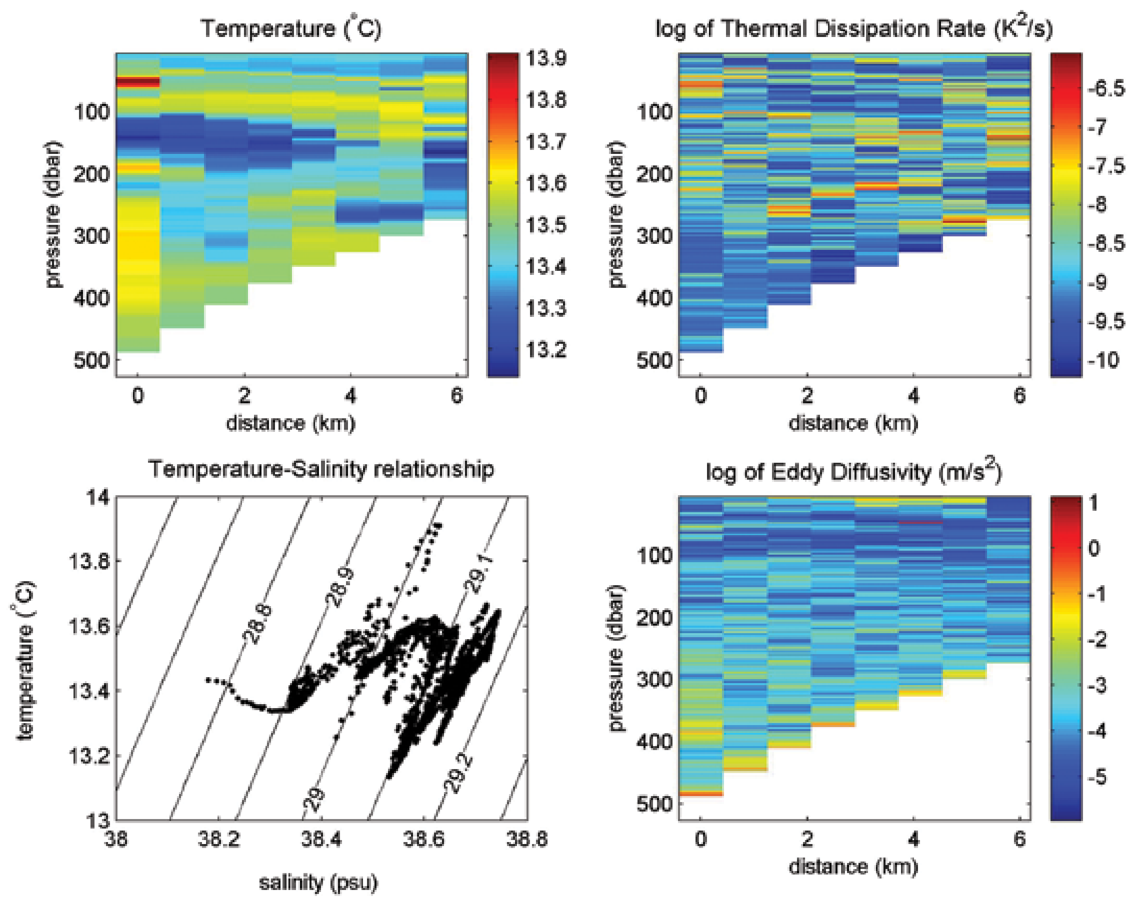

FIGURE 4
Measured temperature (upper left), measured salinity (lower left with potential temperature), calculated thermal dissipation rate from measured microstructure temperature (upper right), and calculated eddy diffusivity from measured current shear (lower right) along a repeated section to the northeast of Bari Canyon (box in Fig. 1). The zig-zag structures along isopycnals (contours of constant potential density) in the temperature-salinity diagram are characteristics of intrusions and interleaving. The thermal dissipation rates and eddy diffusivity values are displayed using a logarithmic scale.

shown in Fig. 1. The left-hand panels show how temperature and salinity variations in this region combine to interleave waters of similar densities but different temperatures. The SO technique resolves these temperature boundaries well. Interestingly, in this particular case, neither the thermal dissipation rate, nor the eddy diffusivity, the "mixing capability" caused by eddies, are tracking these broader-scale water mass boundaries. The thermal dissipation rate and eddy diffusivity shown in the right-hand panels in Fig. 4 highlight gradients of smaller vertical scale than those observable with SO, thus complementing the SO measurements. Overall, the ADRIASEISMIC-09 exercise provides compelling evidence for the need to gather a full range of measured oceanographic variables to complement and interpret the high-lateral-resolution vertical temperature changes seen with SO.

THE WAY FORWARD

The high-quality ADRIASEISMIC-09 data set we acquired demonstrates that SO can be carried out from oceanographic vessels of medium size with relatively light equipment, and that the seismic approach can be performed also in relatively shallow basins. This is an important finding, as the use of a large seismic vessel would have prohibited the kind of oceanography sampling that is necessary for any study characterizing dense shelf water movement.

SO is now at a turning point in its development. NRL and others have demonstrated that high-resolution SO observations are possible, but two aspects will likely determine if SO will be incorporated as a practical, standard research or operational oceanographic tool: (1) development of optimal field parameters and (2) development of signal processing. Field acquisition parameters such as source strength, streamer length, and others will affect the ease of deployment, quality of the data, weather windows, and the level at which SO and more familiar physical oceanography measurements might interfere with each other.[11] Also, SO records are so different from existing oceanographic records that to optimally incorporate them with CTD data, sea surface temperature measurements from satellites, turbulence measurements, and other data has required, and will require, significant algorithm development.[5,6,12,13] Although some important achievements have been made in qualitatively interpreting SO data, the full potential to use this new view of the ocean's thermal structures to quantitatively address questions on ocean dynamics has yet to be realized. To this end, the ADRIASEISMIC-09 dataset is a very important resource. For the first time, all applicable ocean variables were sampled at very high resolution together with seismic images, allowing us to explore the limits and capabilities of seismic methods for characterizing various ocean processes.

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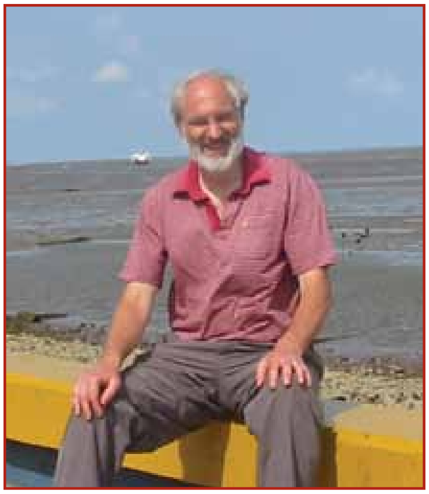

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