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COMMENTARY

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Key Points:

- This paper contributes to the "missing mixing" problem. It is a maturation of seismic oceanography into a standard oceanographic tool
- There is much yet to do in seismic oceanography, and great promise, but the growth of the field has stalled out
- Equipment size, expense, power, and regulations limited growth. Equipment designed specifically for water column work might help

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Seismic Oceanography's Failure to Flourish: A Possible Solution

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Abstract A recent paper in *Journal of Geophysical Research: Oceans* used multichannel seismic observations to map estimates of internal wave mixing in the Gulf of Mexico, finding greatly enhanced mixing over the slope region. These results suggest that the ocean margins may supply the mixing required to close the global thermohaline circulation, and the techniques demonstrated here might be used to map mixing over much of the world's continental shelves. The use of multichannel seismics to image ocean phenomena is nearly 15 years old, and despite the initial promise, the techniques have not become as broadly used as initially expected. We discuss possible reasons for this, and suggest an alternative approach that might gain broader success.

Plain Language Summary Holbrook et al. (2003) clearly showed that sharp temperature contrasts in the ocean could be imaged with standard geophysical equipment, giving wonderful pictures of ocean fronts, eddies, internal waves, and horizontal mixing via layers of water that intrude across the fronts. Dickinson et al. (2018) used this imaging technique to map the strength of vertical mixing by internal waves, and showed us that the mixing rate is tens and even hundreds of times larger on the continental slopes of the Gulf of Mexico, than in the open Gulf. This matters because vertical mixing controls the amount of heat transported poleward via the "global ocean conveyor belt," and our present understanding suggests that the mixing should be much stronger than most of our direct observations of turbulent mixing (in the main thermoclines) have found. If their findings can be extended to the rest of the globe, it tells us that the ocean "edges" are where the important vertical mixing is occurring. It is worth checking other locations to see if the same results are found. The acoustic imaging techniques used by Dickinson et al. (2018) are like satellite images in that they trade the accuracy of direct physical measurement for the overview of large-scale coverage. In addition to internal waves, these images also show a huge variety of ocean phenomena involved in ocean circulation and mixing: fronts, eddies of various kinds, and intruding layers of water related to mixing across the fronts and eddies. They are undoubtedly important in the mixing picture, and the images show us how the different phenomena connect. Despite this promise, the approach has not been as widely adopted as first expected, probably because of the large and expensive equipment, and powerful sound sources that require careful regulation. An approach with more modest goals, using a "speaker"-type sound source emitting weaker smooth signals instead of strong pulses, and shorter towed strings of microphones, would allow an acoustic visualization system to be mounted on standard oceanographic ships to give us images that show us what is going on beneath us as we move from place to place during our field studies. Maybe the more general availability of subsurface images of ocean phenomena that directly relate to researchers' field observations will allow broader familiarity and acceptance of the techniques.

1. Introduction

Dickinson et al. (2018) used multichannel seismic (MCS) imaging techniques to track water column reflectors (primarily locations of large dT/dz) and tracked their undulations to give valuable information on the internal wave field and associated mixing. They inferred greatly enhanced mixing over the continental slope in the Gulf of Mexico, giving valuable clues about the problem of "missing mixing": our knowledge of thermohaline circulation suggests a much larger average diapycnal diffusivity than mixing observations in the ocean thermocline can account for. Although acoustically tracked water column reflectors have been used to infer oceanic mixing rates before (Holbrook et al., 2013; Sheen et al., 2009), this work is distinguished by a careful analysis of the many assumptions and errors inherent to the method, and it thus marks a maturation of seismic oceanography (SO) into a "standard" tool that can quantitatively map internal wave diapycnal mixing rates. It is worth doing this in a variety of regions, *with standardized methodology*, to obtain broad space-time coverage. And any opportunity to test this methodology against other mixing measures should be taken. Despite this, there is much more to do:

- While reflector slopes can be interpreted as isopycnal slopes in areas with a tight T-S relationship, they cannot in the presence of thermohaline intrusions. What are the errors as a function of thermohaline structure? We do not have a clear answer yet.
- We should go beyond using fits to an assumed model spectrum. Deviations from that model could indicate unusual and exciting physics! In addition to fitting to model spectra, we should watch for systematic deviations and learn their cause.
- The images are *two-dimensional* and contain a wealth of vertical information that has yet to be exploited. This information may yield information on internal wave vertical wave number spectra and associated internal wave strain, allowing more incisive looks as to how the wave field varies spatially.

2. What Do Seismic Images Show?

MCS systems were designed to visualize subbottom features in the Earth's crust. Powerful air guns emit an impulse that reflects from contrast in impedance (sound speed $\times$ density) and is heard on many towed hydrophones. The returns from multiple hydrophones are processed and filtered to enhance the signal and reduce noise. The resulting images are effectively the convolution of the vertical impedance gradient with the system impulse response, so that we primarily see vertical temperature gradients on the scale of the source waveform, with $\sim$10 to 20% contribution from salinity gradients, (Ruddick et al., 2009; Sallarès et al., 2009). The convolution theorem gives us another way to think of it: the vertical Fourier transform of the seismic image is the transform of the impedance gradient times the transform of the source waveform. Put more simply, sound reflects from thermohaline fine structure gradients with wavelength matching that of the sound, so the system needs to have source content and hydrophone response at frequencies corresponding to the vertical scales of interest; i.e., 150 Hz sound reflects from 10 m wavelengths. A broader system bandwidth thus yields more information. For those familiar with laboratory optical techniques, seismic images are directly analogous to Schlieren images (Turner, 1973) of (optical) refractive index gradient.

In addition to undulations associated with internal waves, SO images show an astounding variety of ocean phenomena including fronts, eddies, submesoscale vortices, thermohaline intrusions and staircases, vertical modes, internal solitons, internal tide beams, turbulent vortices, nepheloid layers, and turbidity currents. It is even possible to estimate geostrophic shear in some situations (Sheen et al., 2011). The extremely detailed *spatial* information in seismic images, as we have already discovered with satellite images of ocean sea surface properties (or laboratory Schlieren images), show qualitatively the connections among these phenomena. Their quantitative nature allows them to be combined with hydrographic data to yield high-resolution sections of both temperature and salinity (Biescas et al., 2014). Since thermal and haline contrasts begin at global scale and are dissipated at microscales (Figure 1), SO can show us how thermal and haline variance passes through these physical phenomena enroute to turbulent and molecular dissipation. The synoptic nature of these images reveals qualitative as well as quantitative clues about the lateral and diapycnal cascade of ocean mixing.

3. Why Has the Growth of the Field Stalled?

In a seminal paper, Holbrook et al. (2003) clearly showed the correspondence between reflections and thermal gradients, and begun this interdisciplinary new field. Existing "legacy" data were reanalyzed and combined with any available physical oceanographic measurements to build knowledge of what oceanographic phenomena could be imaged. In November 2008, the first ESF Exploratory Workshop in Seismic Oceanography was held in Begur (Spain), with around 100 participants from 10 or more countries, and initial results from a landmark observational/intercomparison project (geophysical oceanography [GO]) were presented. This meeting had a roughly 50/50 mix of geophysicists and physical oceanographers, and a majority of the physical oceanographers had some experience in laboratory fluid dynamics—experience that allowed them to appreciate the usefulness of spatially oriented synoptic information. Holbrook (2013) expressed

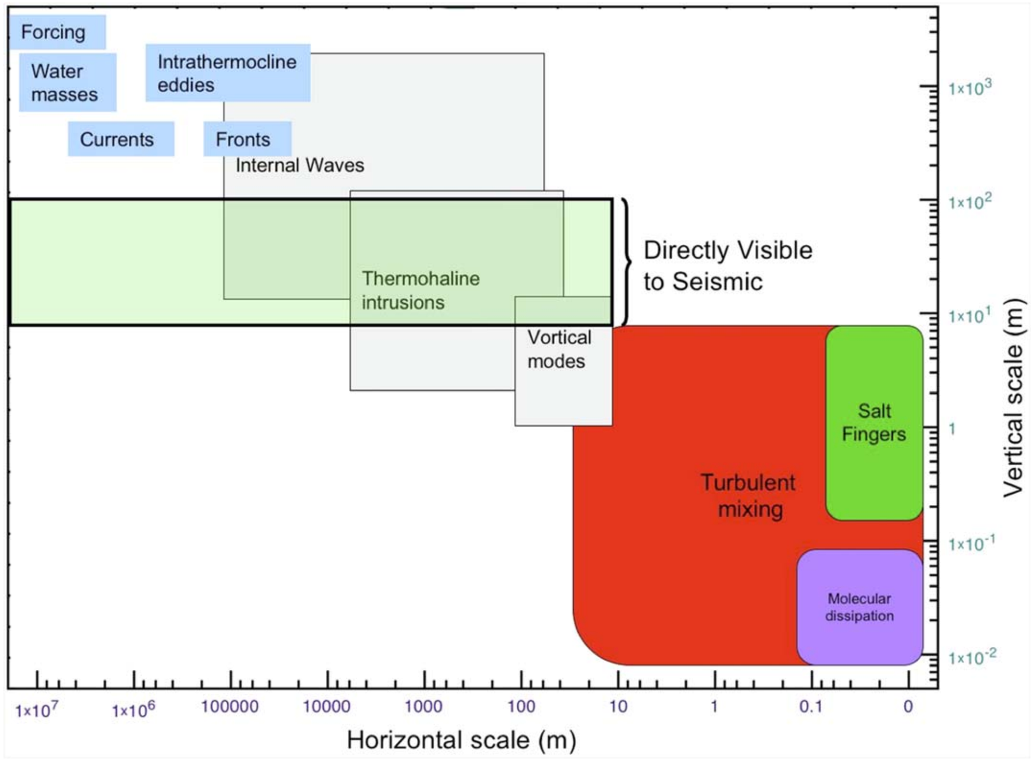

Figure 1. A cartoon showing the (log-log) scale ranges of the physical phenomena involved in the cascade of thermal and haline variance. Thermohaline contrasts enter the ocean at large scales (top left) and are passed to successively smaller and smaller scales until molecular diffusion erases them (purple box at bottom right). MCS images the range of scales in the light green box and illuminates the phenomena and the spatial relationships among them.

disappointment at the failure of SO to become a standard tool for oceanographers, and he suggested the barriers are perceived cost of acquisition and disciplinary boundaries. Although he made suggestions to help advance the field, the growth of SO in the past 5 years has stalled, with relatively few North American researchers remaining active in the field.

Why has not SO, nearly 15 years old, grown as initially expected? Probably because acquiring MCS data is cumbersome, expensive, and very closely regulated, and the interdisciplinary gap makes it too difficult to collaboratively overcome these disadvantages. MCS systems use powerful air gun sound sources, ~10 km long hydrophone strings, specialized large vessels, and because of the source intensity, a careful approval process, and restrictive operating protocol designed to minimize harm to aquatic life. The size of the equipment limit both vessel mobility and the ability to take concurrent ancillary observations: expendable probes are feasible but CTDs are not. These issues plus the expense tend to restrict acquisition of new MCS data to specialized geophysical surveys, with water column observations being an afterthought at best. Because oceanography and geophysics are distinct fields, usually with distinct funding channels, it is rare for oceanographers to enter into collaborations within geophysical surveys. The science is usually driven by the sub-bottom geophysics, not the oceanography. It is often just too difficult to reach across disciplinary boundaries in order to set up collaborations.

4. How Might We Fix This?

I think a more modest system specific to water-column use might allow broader oceanographic use. Instead of large air guns emitting strong pulses, a smaller, coherent spread-spectrum source (underwater speaker) would emit a lower intensity waveform over several seconds. A relatively short (~500 m) string of hydrophones would deploy automatically when the vessel is underway, giving near real-time imagery to guide fieldwork, and also would be recorded for detailed analysis. A coherent sound source has several advantages over conventional air gun sources for MCS data acquisition:

1. The coherent source signal is spread over a much longer time than the impulse from an air gun, allowing the peak sound pressure to be tens of decibels lower, with potential for reduced effect on marine life, and to reduce the regulatory issues (Weilgart, 2012).
2. The coherent source signal can have pseudorandom components, which would appear more like background noise to marine life, and may reduce sensitivity of the resulting seismic images to periodic constituents (i.e., multiple layers) in the ocean reflectivity (Weilgart, 2012).
3. The improved knowledge of the source characteristics allows more precise deconvolution to be used in signal detection.
4. The source signal can be optimally shaped to minimize side lobe effects.
5. Knowledge of the expected reflectivity spectrum and background noise spectrum permits adjustment of the source frequency content to optimize the received signal-to-noise ratio.
6. The ability to randomize source signals allows successive emissions to be arranged to minimize cross talk between different reflections.

Optimal waveform, intensity, frequency range, and sound source and hydrophone characteristics would need to be determined, and there will likely be compromises that limit the depth and intensity of what structures can be seen. But acquiring "mini-MCS" data as an integral part of oceanographic expeditions would give real-time imagery of thermohaline structures, and even better results with postprocessing techniques like direct waveform inversion. It is currently feasible to simulate such systems, and we could use existing data sets to improve and optimize their design. It would be wonderful if such a system could be prototyped, and then set up to become a community facility.

5. Conclusions

Despite stunted growth, SO is not dead. There will be a session on the topic at the February AGU/ASLO Ocean Sciences meeting in Portland at which the organizers will give a tutorial on the principles and promise of SO. (T009: Seismic Oceanography: What can active-source seismic reflection profiling tell us about the oceanic water column? Session ID#: 27826, 2018, AGU/ASLO Ocean Sciences meeting, February 11–16, Portland OR.) Feel free to drop by.

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