The Next Decade of Seismic Oceanography: Possibilities, Challenges and Solutions

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Seismic reflection profiling of thermohaline structure has the potential to transform our understanding of oceanic mixing and circulation. This profiling, which is known as seismic oceanography, yields acoustic images that extend from the sea surface to the sea bed and which span horizontal distances of hundreds of kilometers. Changes in temperature and salinity are detected in two, and sometimes three, dimensions at spatial resolutions of $\sim O(10)$ m. Due to its unique combination of extensive coverage and high spatial resolution, seismic oceanography is ideally placed to characterize the processes that sustain oceanic circulation by transferring energy between basin-scale currents and turbulent flow. To date, more than one hundred research papers have exploited seismic oceanographic data to gain insight into phenomena as varied as eddy formation, internal waves, and turbulent mixing. However, despite its promise, seismic oceanography suffers from three practical disadvantages that have slowed its development into a widely accepted tool. First, acquisition of high-quality data is expensive and logistically challenging. Second, it has proven difficult to obtain independent observational constraints that can be used to benchmark seismic oceanographic results. Third, computational workflows have not been standardized and made widely available. In addition to these practical challenges, the field has struggled to identify pressing scientific questions that it can systematically address. It thus remains a curiosity to many oceanographers. We suggest ways in which the practical challenges can be addressed through development of shared resources, and outline how these resources can be used to tackle important problems in physical oceanography. With this collaborative approach, seismic oceanography can become a key member of the next generation of methods for observing the ocean.

Keywords: seismic oceanography, acoustic imaging, observational oceanography, submesoscale, internal waves, turbulent mixing, benchmarking, standardization

1 INTRODUCTION

During the twentieth century our knowledge of oceanic circulation was revolutionized by a host of observational tools. Probes descended beneath the waves to measure the temperature, composition and movement of seawater at great depths, whilst swarms of floating sensors drifted with the currents (e.g., Jacobsen, 1948; Swallow, 1955; Gregg and Cox, 1971; Davis et al., 1992). Colorful dyes

and inert chemicals illuminated the structure of internal waves and the mixing of water masses, and satellite-borne instruments mapped the shape and temperature of the sea surface from space (e.g., Woods, 1968; Born et al., 1979; Ledwell et al., 1986). Measurements made by these, and many other, tools showed that oceanic flow is not governed solely by currents that span thousands of kilometers and which vary on time scales of decades. Instead, circulation is maintained by a constant exchange of energy between global currents and turbulent motions, which mix water over distances of millimeters on time scales of seconds (e.g., Wunsch and Ferrari, 2004; Moum, 2021).

Improved understanding of this exchange is vital to modeling of the ocean's ability to store heat and carbon, and thus to efforts to mitigate the effects of climate change (MacKinnon et al., 2017; Whalen et al., 2020; Richards et al., 2021). However, characterizing the disparate, intermittent and continuously evolving processes that drive circulation has proven challenging. The majority of observational systems are limited to providing time series at a single location, to acquiring measurements in a single spatial direction or along a single travel path, or to monitoring only the surface of the ocean (e.g., moored arrays, probes dropped from a ship, and satellite instruments, respectively; van Haren, 2018). Few observations are available from abyssal regions of the ocean that are thought to play a critical role in controlling mixing of water masses and in modulating climate change (e.g., de Lavergne et al., 2016; Desbruyères et al., 2016; Desbruyères et al., 2017; Levin et al., 2019). Key dynamical phenomena, such as submesoscale currents and lee waves, occur on time and length scales that are not well sampled by common observational tools (e.g., McWilliams, 2016; Legg, 2021).

Seismic reflection profiling[1] of thermohaline structure offers a solution to several of the challenges of ocean observation. This profiling, known as seismic oceanography, is carried out by a ship towing a source of acoustic energy and one or more cables of hydrophones a few meters below the sea surface (**Figure 1A**; Sheriff and Geldart, 1995). At periodic intervals the acoustic source is fired, exciting water-column sound waves by release of either compressed air or electrical charge. Reflection of these waves from changes in temperature and salinity at depth is recorded by the hydrophones. Using these reflections, the properties of thermohaline structure can be investigated.

Use of underwater sound for remote sensing of internal oceanic structure is, of course, not new. For decades, ocean-bottom echosounders have monitored thermocline depths, acoustic tomographic systems have detected basin-wide temperature changes, and acoustic Doppler current profilers (ADCPs) have measured current velocities (Rossby, 1969; Munk and Wunsch, 1979; Pinkel, 1979). High-frequency (i.e., $\gtrsim$ 10 kHz) acoustic surveys provide spectacular images of near-surface internal waves and capture the intensity of turbulent mixing (**Figures 2B, C**; e.g., Proni and Apel, 1975; Geyer et al., 2010; Lavery et al., 2013). Seismic oceanography is distinguished,

however, from other acoustic imaging methods in two ways (Fer and Holbrook, 2009). First, it uses low-frequency (i.e., $\lesssim$ 100 Hz) sound that does not attenuate rapidly with depth[2]. Second, each imaged point is repeatedly sampled over a time interval of $\lesssim$ 30 minutes by different configurations of acoustic source and hydrophones, increasing the signal-to-noise ratio (**Figure 1B**). These distinctive features lend seismic oceanography a unique combination of three key characteristics:

- **Multi-dimensional observation of the ocean at high spatial resolution.** Seismic oceanography provides a two-dimensional, and often three-dimensional, view of the ocean at horizontal and vertical resolutions on the order of 10 m. Other observational tools may achieve higher spatial resolutions, but usually provide measurements in only one dimension.
- **Penetration to abyssal depths.** Unlike higher-frequency acoustic methods, seismic oceanography captures thermohaline structure down to depths of several kilometers. This capability allows observation of abyssal regions that are otherwise undersampled.
- **Horizontal coverage over hundreds of kilometers.** Seismic data are continuously recorded along $\lesssim$ 1,000-km-long transects. This coverage provides a holistic view of structures such as eddies that are otherwise only intermittently sampled (e.g., by dropped probes).

Due to these characteristics, seismic oceanography has provided uniquely detailed images of features such as fronts, tidal beams, eddies, thermohaline staircases and turbid layers (e.g., Nakamura et al., 2006; Holbrook et al., 2009; Pinheiro et al., 2010; Fer et al., 2010; Vsemirnova et al., 2012; **Figure 2D**). Importantly, seismic records provide not only spectacular images, but have yielded quantitative insight into dynamical phenomena including thermohaline interleaving, propagation of internal waves, and turbulent mixing (e.g., Papenberg et al., 2010; Tang et al., 2014; Falder et al., 2016; **Figure 3**). Reviews of topics as wide-ranging as stratified turbulence, circumpolar currents and submesoscale flow have cited results from seismic oceanography (e.g., Riley and Lindborg, 2008; Thompson et al., 2018; McWilliams, 2019). In total, more than one hundred peer-reviewed research papers have now presented seismic oceanographic data (**Appendix A; Table A**; see **Supplementary Material** for all appendices and tables).

Despite these successes, seismic oceanography has struggled to establish itself as a standard observational tool. This slow development has two causes. First, the field has been hindered by practical challenges associated with acquiring data and with analyzing records in a consistent and reliable way. Second, and more fundamentally, many physical oceanographers regard the field as a curiosity, with no clear vision or scientific application. To progress further, the seismic oceanographic community needs to identify key scientific questions that it can systematically address.

Here, we discuss the practical challenges that face seismic oceanography and suggest ways in which they can be overcome

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[1] In seismic acquisition, the term *profile* describes a two-dimensional map plotted against range and depth. Here, we instead use the oceanographic term *section*. Our use of the term *profile* is limited to description of a one-dimensional series of measurements recorded as a function of depth (Krahmann et al. 2008).

[2] A small number of seismic oceanographic surveys have used sound with frequencies as high as ~ 500 Hz (see *Section 2.1.1*; Ker et al., 2015). However, the great majority have used low-frequency sound.
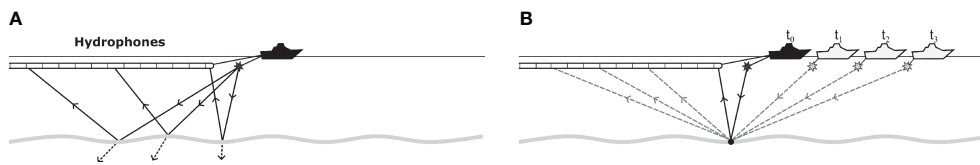
FIGURE 1 | Principles of seismic oceanography. **(A)** Cartoon showing single release of energy by acoustic source. Black star = acoustic source; undulating gray line = change in oceanic temperature and/or salinity; solid black lines with arrows = travel paths for three example sets of incident and reflected sound waves; dashed black lines with arrows = transmitted sound waves. In reality, sound waves travel out from acoustic source in all directions and are recorded at every hydrophone along cable. **(B)** Cartoon illustrating repeated sampling of same spatial point by multiple firings of acoustic source. Black dot = repeatedly sampled point; black star = acoustic source at time t_0; solid black lines with arrows = travel path for sound waves excited at time t_0 and reflected from black dot; gray stars = acoustic source at later times t_1, t_2, t_3; dashed gray lines with arrows = travel paths for sound waves excited at times t_1, t_2, t_3 and reflected from black dot. Note that cable of hydrophones is not illustrated for times t_1, t_2, t_3. For more complete introductions to acquisition of seismic oceanographic data, see Fer and Holbrook (2009), Ruddick et al. (2009) and Holbrook (2009).

(*Section 2*). We then discuss how seismic oceanography can address scientific questions that other tools cannot answer (*Section 3*). Finally, we outline ways in which the seismic oceanographic community can implement these solutions by agreeing on priorities and by working together on collaborative projects (*Section 4*).

2 HOW CAN SEISMIC OCEANOGRAPHY OVERCOME ITS PRACTICAL CHALLENGES?

Seismic oceanography is faced by three practical challenges. Previous works have outlined possible solutions to one or more of these challenges (e.g., Jones et al., 2008; Holbrook, 2009; Jones et al., 2010; Buffett and Carbonell, 2011; Ruddick, 2018). Here, we build on these works to develop a comprehensive strategy for overcoming all three challenges.

2.1 How Can We Acquire Seismic Oceanographic Data?

Perhaps the greatest practical obstacle to further development of seismic oceanography is the logistical difficulty and high cost of acquiring data. Conventional seismic reflection surveys require specialized vessels that are capable of towing powerful acoustic sources and long cables of hydrophones. A small number of research bodies maintain such vessels (e.g., the Alfred Wegener Institute, Germany; the Natural Environmental Research Council, UK; the University-National Oceanographic Laboratory System, USA). Access to ship time is limited and surveys are up to five times more expensive than other ocean-going research cruises (National Research Council, 2015; National Science Foundation, 2016). Chartering of independent seismic exploration companies can cost up to three times as much again (National Science Foundation, 2016). There are two possible solutions to the challenge of high cost and logistical difficulty.

2.1.1 Development of New Seismic Systems

First, data could be acquired using systems that are specially designed for seismic oceanography (e.g., Ruddick, 2018). These

systems could be optimized to reduce costs and to target specific oceanographic phenomena. Ideally, they would be deployed alongside other observational instruments and would not require use of specialized vessels. The most obvious way to lower costs and improve deployability is to use weaker acoustic sources and shorter cables of hydrophones. Weaker acoustic sources produce higher-frequency (i.e., $\gtrsim$ 100 Hz) sound waves that provide increased spatial resolution, but the signal-to-noise ratio degrades more quickly with depth (Geli et al., 2009; Hobbs et al., 2009). Although this degradation can be partially compensated for by more frequent firing of the source and by a denser spacing of hydrophones, it seems unlikely that higher-frequency sources will be capable of clearly imaging the water column to abyssal depths (Nakamura et al., 2006). Instead, higher-frequency seismic systems could be optimized for imaging of relatively shallow structures such as seasonal thermoclines (Piété et al., 2013; Ker et al., 2015; Sallares et al., 2016; Mojica et al., 2018). When combined with direct measurements of properties such as temperature and salinity, they could form an excellent tool for investigation of processes that are too coarse to be detected by high-frequency echosounders and yet too fine to be detected by conventional seismic systems.

2.1.2 Use of Existing Datasets

An alternative solution to the difficulty of acquiring new seismic reflection data is to analyze existing records. An overwhelming majority of these records have been acquired by seismic exploration companies, which spend billions of dollars each year on new datasets (McBarnet, 2013). As a consequence, these companies can afford equipment and modes of operation that are far beyond the budgets of research organisations. Commercial seismic records are thus likely to have higher signal-to-noise ratios and to be more accurately spatially positioned than records acquired for scientific research. Dense layouts of overlapping transects are often acquired in a small area over a period of several weeks or months, allowing the temporal evolution of oceanographic phenomena to be tracked (e.g., Dickinson et al., 2020; Gunn et al., 2020b; Zou et al., 2020; Gunn et al., 2021). Many commercial exploration vessels carry several parallel cables of hydrophones, enabling imaging of thermohaline structure in three spatial dimensions (these
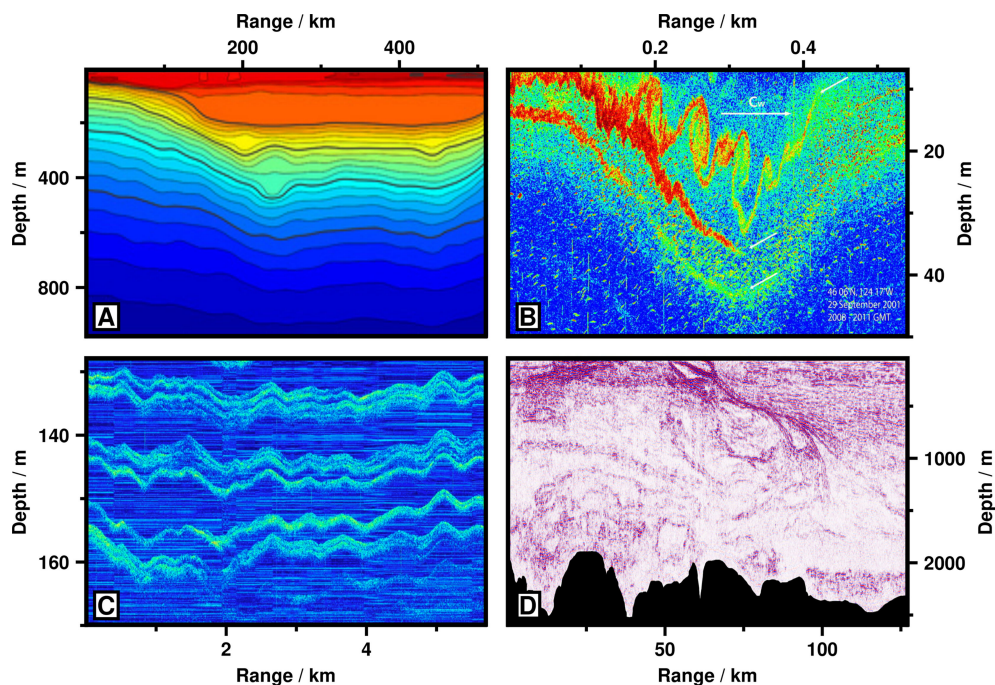
FIGURE 2 | Comparison of seismic oceanography to other observational techniques. **(A)** Temperature section interpolated from measurements made by glider in Gulf of Mexico (after Figure 3D of Meunier et al., 2019). Red = warmer water; blue = cooler water; vertical resolution ≈ 2 m; horizontal resolution ≈ 2,000 m. **(B)** High-frequency (∼ 120 kHz) echosounder image of Kelvin-Helmholtz instabilities within internal solitary wave above Oregon continental shelf (after Figure 14 of Moum et al., 2003). Red = high acoustic intensity; blue = low acoustic intensity; vertical resolution ≈ 0.04 m; horizontal resolution ≈ 3 m at depth of 30 m. **(C)** High-frequency (∼ 15–25 kHz) echosounder image of thermohaline staircase in Arctic Ocean (after Figure 5 of Stranne et al., 2017). Brighter colors indicate higher acoustic amplitudes; vertical resolution ≈ 0.1 m; horizontal resolution ≈ 15 m at depth of 150 m. **(D)** Seismic oceanographic image of oceanic front at Brazil-Malvinas Confluence (after Figure 3A of Gunn et al., 2020b). Red colors = positive acoustic amplitudes; blue colors = negative acoustic amplitudes; black region = seafloor; vertical and horizontal resolutions ∼ O (10) m. Note different ranges and depths of four panels.

surveys are known as three-dimensional; Blacic and Holbrook, 2010; Bakhtiari Rad and Macelloni, 2020; Zou et al., 2021).

Existing surveys are concentrated above continental shelves and slopes, which exploration companies have targeted since they house economically valuable reserves of oil and gas (**Figure 4A**). Recent observational, theoretical and computational work suggests that the mixing that drives oceanic circulation is most intense above these continental margins and above other topographically rough features such as mid-ocean ridges and seamount flanks (e.g., Waterhouse et al., 2014; Ferrari et al., 2016; McDougall and Ferrari, 2017; Drake et al., 2020). Continental margins also host western boundary currents that transport significant quantities of heat, salt and nutrients (e.g., Stommel, 1948; Hu et al., 2015; Buckley and Marshall, 2016). In a warming climate, the intensity and position of these currents is likely to change markedly, yet there are limited direct observations of their magnitude and variability (e.g., Wu et al., 2012; Yang et al., 2016). Existing seismic records span several decades and provide a dataset of unprecedented size and coverage that can be used to investigate in detail these critically important interactions above continental margins.

Thanks to burgeoning open-access initiatives, an increasing number of both academic and commercial datasets are being made publicly available (**Figures 4B, C**; **Appendix B**). Researchers need only cover data-dearchiving and data-shipment

costs. Access to other, privately held, commercial datasets might be most easily gained through formation of an international collaboration for all seismic oceanography researchers (Jones et al., 2010; Buffett and Carbonell, 2011). Many seismic exploration companies are currently seeking ways to improve their public image by promoting independent scientific research. Supporting seismic oceanography is particularly attractive since only commercially worthless water-column reflections, and not commercially valuable subsurface reflections, need be supplied.

2.2 How Can We Benchmark Seismic Oceanographic Data?

Estimation of accurate quantitative results from seismic oceanographic datasets requires a reliable understanding of the correspondence between seismic records and hydrographic properties. However, it has remained difficult to gain such an understanding since the strength and form of recorded seismic amplitudes are functions of many variables, which depend both on local thermohaline structure and on the seismic acquisition system. Key questions fall into three areas:

- **Hydrographic sensitivity:** What are the smallest changes in temperature and salinity which seismic reflection surveys can detect? How well do these changes correspond to changes in
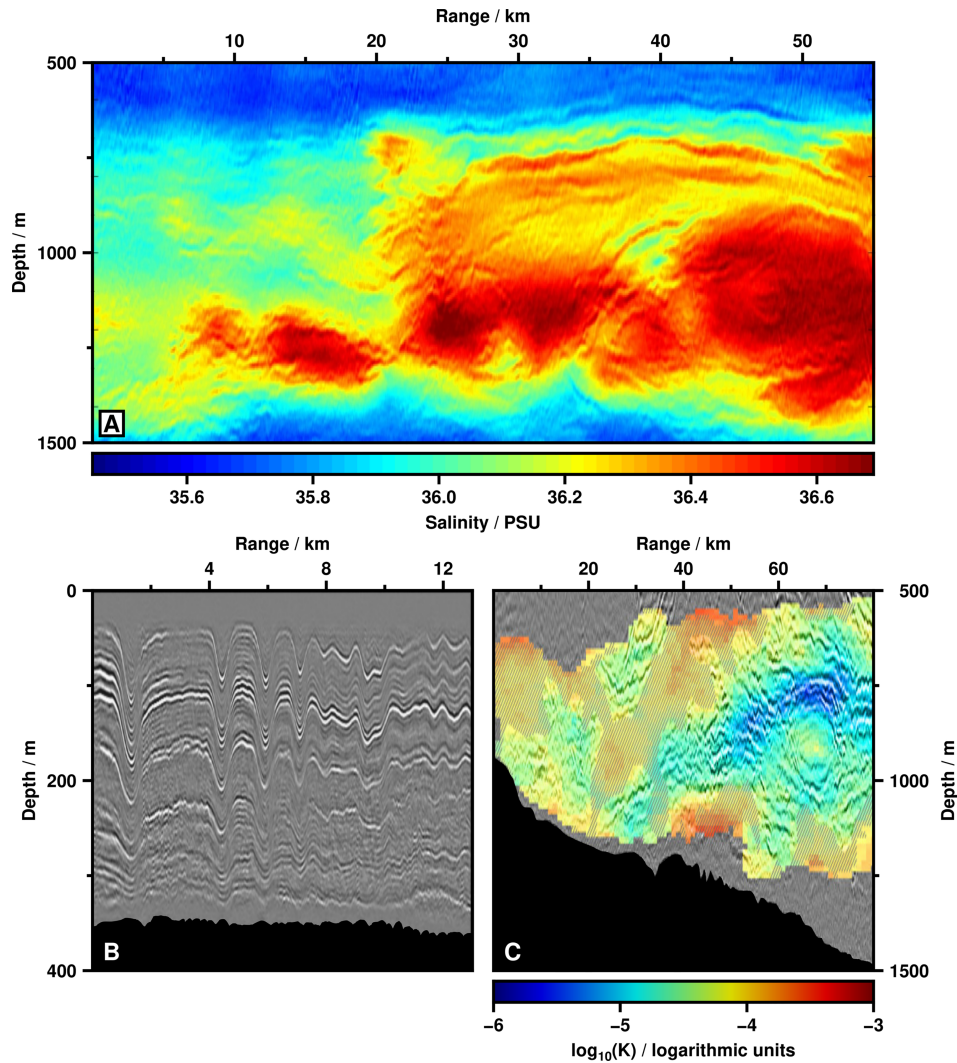
FIGURE 3 | Initial successes of seismic oceanography. **(A)** Values of salinity inverted from seismic oceanographic image of eddy of Mediterranean Water in Gulf of Cadiz (after Figure 6 of Dagnino et al., 2016). Note finely resolved layering along upper side of eddy. **(B)** Internal solitary waves captured in seismic oceanographic image from South China Sea (after Figure 2 of Tang et al., 2016). Grayscale represents response of thermohaline structure to seismic waves; black region = seafloor. Internal-wave velocities can be estimated from seismic records. **(C)** Spatial map of diapycnal diffusivity, K, estimated from seismic oceanographic image above Falkland Plateau (after Figure 15b of Falder et al., 2016). Grayscale = seismic image; colored overlay = estimates of K; hashed pattern = areas where estimates are less certain; black region = seafloor. Note depressed values of K above eddy imaged at range of ∼ 60–70 km.

density? On what spatial length scales can these changes be detected?

- **Temporal blurring:** How does motion of thermohaline structure, acoustic source and recording system affect observation of features that are repeatedly sampled during periods of ≲ 30 minutes?
- **Seismic system:** How do the answers to these questions change with variations in acoustic frequency and in design of the recording system?

Studies have addressed one or more of these questions in isolated circumstances (**Appendix C; Table C**). To analyze seismic data more widely, it would be helpful to systematically investigate these questions across the full range of oceanographic settings. This investigation can be carried out in two ways.

2.2.1 Field Datasets With Hydrographic Calibration
First, seismic records can be compared to coincident, direct measurements of properties such as temperature, salinity and current velocity. These comparisons aid interpretation of imaged phenomena and guide estimation of quantities such as temperature, salinity and diapycnal diffusivity from seismic images (e.g., Papenberg et al., 2010; Holbrook et al., 2013). Coupling seismic records to more familiar oceanographic measurements is also likely to encourage widespread acceptance of seismic oceanography (Ruddick, 2018). Twenty-four existing datasets have such ancillary
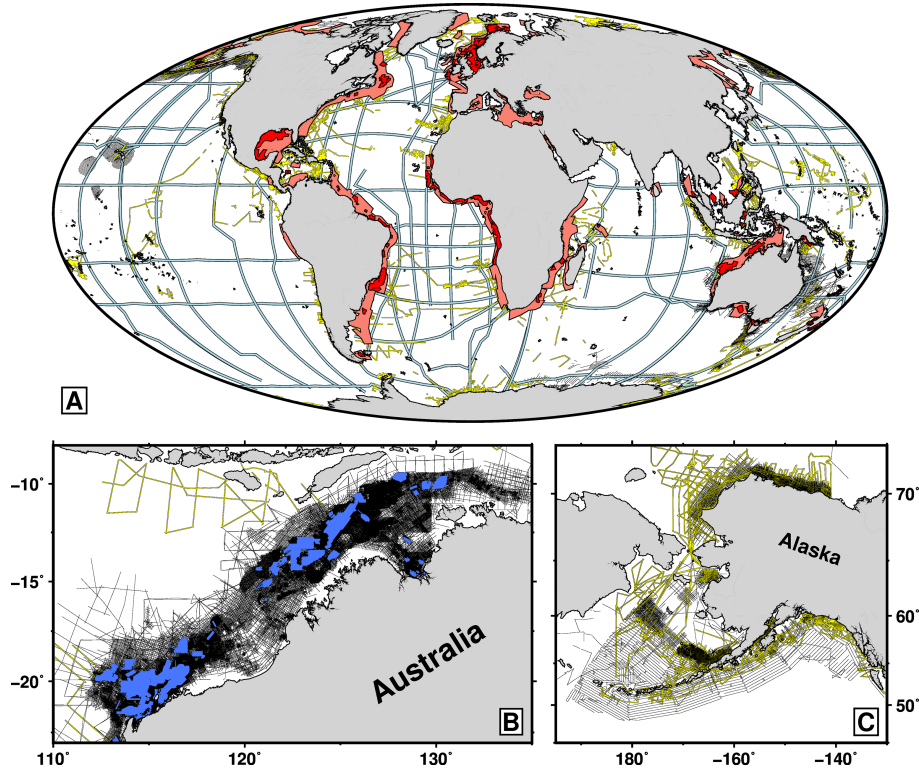
FIGURE 4 | Existing marine seismic reflection data. **(A)** Global distribution. Light red polygons = regions covered by two-dimensional (i.e., single-cable) surveys acquired by seismic exploration companies; dark red polygons = regions covered by three-dimensional (i.e., multi-cable) surveys acquired by seismic exploration companies; thin black lines = publicly available two-dimensional surveys acquired by seismic exploration companies in other regions; yellow lines = publicly available two-dimensional surveys acquired by research institutions; light blue lines = hydrographic transects of World Ocean Circulation Experiment (WOCE; www.ewoce. org). Red polygons were traced from the websites of the five largest exploration companies (CGG, ION, PGS, Schlumberger, TGS) and represent > 6.3 million km of two-dimensional seismic data and > 5.5 million km^2 of three-dimensional seismic data. Publicly available data were downloaded from a range of online repositories (note that plotted transects represent only a small subset of all existing data). **(B)** Zoom of Australia's Northwest Shelf showing only publicly available seismic data. Blue polygons = three-dimensional commercial surveys made available through the National Offshore Petroleum Information Management System (NOPIMS; www. ga.gov.au/nopims). **(C)** Zoom of the Gulf of Alaska and the Bering, Chukchi and Beaufort Seas showing only publicly available seismic data. Note that WOCE transects are not plotted in panels **(B)** or **(C)**. See **Supplementary Material** for further details of data provenance.

data and have been used for seismic oceanographic research (**Appendix C.1**; **Table C.1**). Datasets with hydrographic calibration could in future be acquired by combining specially designed seismic systems of the kind discussed in *Section 2.1.1* with instruments such as expendable bathythermographs (XBTs), ADCPs, and microstructure profilers. However, seismic exploration companies, which carry out the majority of surveys, do not routinely acquire high-quality hydrographic data. More fundamentally, the unique coverage and spatial resolution of seismic reflection data means that coincident hydrographic measurements cannot capture all relevant scales.

2.2.2 Numerical Modeling
Numerical modeling and synthetic datasets offer a way to comprehensively explore scales that hydrographic calibration cannot access. An ideal numerical model would include realistic descriptions of two elements. First, thermohaline structure would be described by a time-variant fluid-dynamical model that resolves time scales of minutes to days and vertical and horizontal length

scales of ∼0(1) m (Ménesguen et al., 2018). Second, this simulated structure would be acoustically probed by a modeled seismic acquisition system travelling at finite speed. Models with these two elements could faithfully replicate the characteristics of seismic surveys in a range of oceanographic conditions.

Existing studies have built numerical models of varying sophistication (**Appendix C.2**; **Tables C.2.1, C.2.2**). These models have been used to investigate the effect of fluid flow on wave propagation and on blurring of seismic reflections, to assess correspondence between reflections and isopycnals, to quantify errors in imaging of deep structure due to non-homogeneous near-surface waters, and to simulate the characteristics of new seismic oceanographic acquisition systems (e.g., Vsemirnova et al., 2009; Ji and Lin, 2013; Holbrook et al., 2013; Ji et al., 2013; Biescas et al., 2016). Previous work must now be built upon to form a standardized toolkit for modeling of seismic reflection profiling of thermohaline structure. Using this toolkit, the accuracy of quantitative results derived from seismic images can be assessed.

2.3 How Can We Analyze Seismic Oceanographic Data?

Development of seismic oceanography has to date been advanced by disparate groups of researchers, each of which has developed its own computer codes for signal processing and interpretation. Many of these codes either rely on proprietary software or have not been made publicly available (see **Table D**). Lack of open-source code hampers replication of results and discourages scientists who do not have a background in seismic signal processing.

To realize the full potential of seismic oceanography, the community must now develop standardized open-source codes which can be used with a broad range of seismic datasets. Key to standardization will be rigorous investigation of the effects of different workflows on the accuracy of results (see **Appendix D** for a discussion of workflows for constructing seismic images). Here, we focus on three fields that comprise the majority of existing quantitative work and which are ripe for standardization:

- **Hydrographic Inversion.** Estimation of sound speed, temperature, salinity and density.
- **Propagation of Internal Waves.** Characterization of the size, velocity and decay of internal waves.
- **Spectral Analysis.** Analysis of internal waves and turbulence using wavenumber spectra.

For each of these fields, we summarize previous work, suggest potential future applications, and highlight selected outstanding questions.

2.3.1 Hydrographic Inversion

Propagation of low-frequency acoustic waves within the oceanic water column is governed by changes in sound speed and, to a much smaller extent, in density (Ruddick et al., 2009; Sallares et al., 2009). Sound speed can thus be directly estimated from seismic data and mapped into values of temperature and salinity using an assumed temperature-salinity relationship and the hydrographic equation of state (see **Appendix D.1** and **Table D.1** for a summary of proposed methods). Hydrographic inversion has been used, for example, to investigate stirring at baroclinic fronts, to describe temperature variance in turbulent waters above a continental slope, and to reassess heat transport onto the Antarctic shelf (Biescas et al., 2014; Minakov et al., 2017; Gunn et al., 2018). Inversion results can also act as constraints for other calculations that are made using seismic records (e.g., estimation of diapycnal heat flux, Gunn et al., 2021; see *Sections 3.1* and *3.2*). Key questions for further development of hydrographic inversion include:

- How accurate can inversion results be in the absence of nearby hydrographic data? *See* Bornstein et al. (2013), Padhi et al. (2015) *and* Blacic et al. (2016).
- What are the smallest and greatest spatial scales that can be recovered? *See* Blacic et al. (2016), Minakov et al. (2017) *and* Gunn et al. (2018).
- Can useful inversion results be obtained from records in which water-column reflections are very faint or absent?

2.3.2 Propagation of Internal Waves

Seismic oceanographic images often display prominent internal waves, including tidal beams, lee waves and trains of solitary waves (e.g., Holbrook et al., 2009; Eakin et al., 2011; Tang et al., 2015). The velocities of these waves can be estimated by analyzing changes in reflection amplitude during the interval of $\lesssim$ 30 minutes within which a single point is sampled (**Appendix D.2; Table D.2**). This approach has shed light on stirring at oceanic fronts, on the evolution of solitary waves, and on heat transport by intrathermocline eddies (Sheen et al., 2012; Tang et al., 2014; Gunn et al., 2018). Blacic and Holbrook (2010) and Zou et al. (2020) suggest how these analyses could be extended to mapping internal waves in three dimensions. This mapping could greatly improve our understanding of internal-wave-driven mixing of energy and material, which plays a critical role in global climate (e.g., Helfrich and Melville, 2006; Legg, 2021). Outstanding questions for seismic oceanographic estimation of internal-wave velocities include:

- To what extent is it possible to decouple the velocities of internal waves from the velocities of background currents?
- How does the accuracy of estimated velocities vary with duration of observation?
- How sensitive are estimated internal-wave velocities to errors in the profiles of sound speed that are used to spatially reposition reflections? *See* Klaeschen et al. (2009).

2.3.3 Spectral Analysis

In addition to imaging clearly visible internal waves, seismic oceanographic data capture the signals of the background internal wave field and of turbulent motions. These signals have most commonly been analyzed by computing horizontal-wavenumber spectra from the vertical displacements of tracked seismic reflections (e.g., Holbrook and Fer, 2005; **Appendix D.3; Table D.3**). This approach has been exploited to investigate the nature of the dynamical transition from internal waves to turbulence, to link intensity of turbulent overturning to submesoscale structure, and to estimate diapycnal mixing above regions of rough bathymetry (e.g., Falder et al., 2016; Tang et al., 2020; Tang et al., 2021). Fortin et al. (2016) suggest how spectra can be estimated from regions of a seismic image in which reflections cannot be tracked. To develop a consistent and reliable method for spectrally analyzing seismic oceanographic images, the following outstanding questions must be addressed:

- How closely must reflections track isopycnals for results to be useful? What information can be extracted from the spectra of reflections that do not track isopycnals? *See* Meunier et al. (2019).
- How severely are spectra distorted by temporal blurring? *See* Vsemirnova et al. (2009) *and* Falder et al. (2016).
- How are spectra affected by use of different methods for mapping of recorded seismic amplitudes into spatial images? Which method is most appropriate? *See* Fortin and Holbrook (2009) *and* Holbrook et al. (2013).
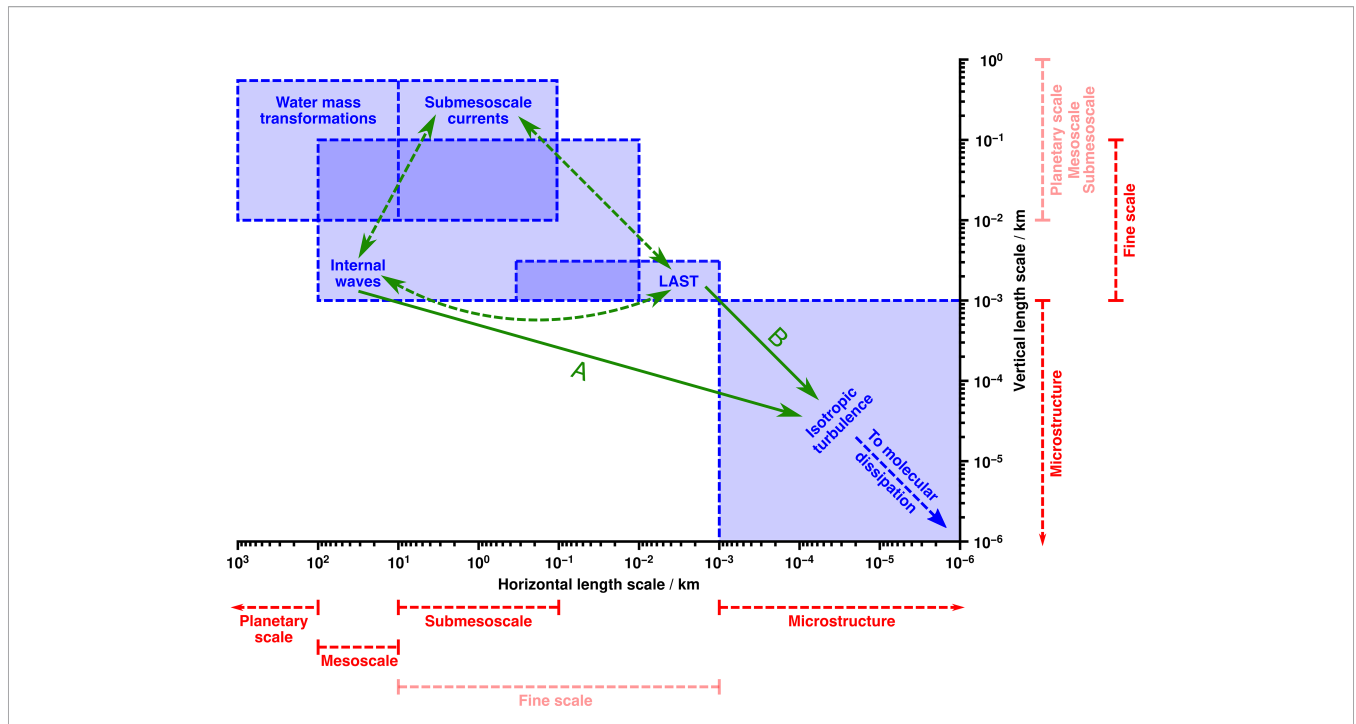
FIGURE 5 | Cartoon showing approximate length scales of processes that can be investigated using seismic oceanography. Red dashed bars show approximate ranges[3] of commonly used descriptive terms. (The term *fine scale* was coined to describe vertically varying structure, and its horizontal extent is not clearly defined. *Planetary scale*, *mesoscale* and *submesoscale* are predominantly used to describe horizontal length scales.) Blue boxes show approximate extents of selected phenomena. LAST = layered anisotropic stratified turbulence[5]. Green arrows show possible parametrizations describing transfer of energy. Solid arrow labeled A = fine-scale parametrizations; solid arrow labeled B = assumption of continuity between LAST and inertial-convective regime of isotropic turbulence[5] ; dashed green arrows = other parametrizations that seismic oceanography could inform. Note that boundaries between phenomena are much more gradational than depicted. Only phenomena referred to in this article are shown. Inspired by Figure 1 of McWilliams (2016) and Figure 1 of Ruddick (2018).

In future, spectra could potentially be computed directly from seismically estimated sections of temperature and salinity, avoiding the need to track reflections (see *Section 3.2*; Xiao et al., 2021).

3 WHAT PROBLEMS CAN SEISMIC OCEANOGRAPHY SOLVE?

To gain widespread acceptance, the seismic oceanographic community must identify ways in which the datasets and tools discussed in *Section 2* can be used to rapidly improve our understanding of oceanic circulation. This circulation encompasses myriad processes that continuously interact on a wide range of time and length scales. No single theory or set of observations can hope to simultaneously capture all of these interactions. Instead, oceanographers conceptualize circulation as a collection of discrete phenomena (e.g., Ferrari and Wunsch, 2009). Transfer of energy between these phenomena is described by parametrizations that are based on a combination of theoretical and empirical evidence (e.g., Garrett, 2006; Polzin et al., 2014; McWilliams, 2017; de Lavergne et al., 2020).

Seismic oceanography straddles a unique combination of scales and is thus ideally placed to revolutionize our understanding of several processes and parametrizations (see

Figure 5). Here, we outline three areas in which the seismic method can provide key insights within the next decade.

3.1 Turbulent Mixing

It is widely accepted that mechanical mixing[4] by turbulent motions is key to maintaining global overturning circulation (e.g., Munk, 1966; Wunsch and Ferrari, 2004). Observations since the 1990s have shown that turbulent mixing is concentrated above regions of rough bathymetry and at the edges of ocean basins (e.g., Polzin et al., 1997; Mauritzen et al., 2002; Naveira Garabato et al., 2019). These observations have spurred theoretical advances which suggest that mixing in narrow boundary layers forms a critical part of oceanic circulation (Levy et al., 2012; Ferrari et al., 2016; McDougall and Ferrari, 2017; Drake et al., 2020). Further measurements are now needed to refine these theories and to tune climate models (e.g., Mashayek et al., 2015; Mashayek et al., 2017; MacKinnon et al., 2017).

Unfortunately, oceanic turbulence is difficult to sample since it is highly intermittent in both space and time (Ivey et al., 2008; Shroyer et al., 2018; Cael and Mashayek, 2021). Fast-response thermistors

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[3]The length scales of depicted descriptive terms and phenomena depend on variables such as latitude, flow velocity, and density structure. For instance, the term *submesoscale* was coined to describe flow on horizontal length scales shorter than the first baroclinic radius of deformation (McWilliams, 1985). For further discussion see Vallis (2017) and Meredith and Naveira Garabato (2022).

and shear probes, which have most commonly been deployed as vertically dropped microstructure profilers, resolve isotropic turbulent[5] fluctuations on length scales as small as $\sim O(1)$ mm (**Figure 5**; e.g., Schmitt et al., 1988; Lueck et al., 2002; Lozovatsky et al., 2019). However, microstructure profiles are uncommon and sparsely distributed. For instance, in compiling a global database of turbulence measurements, Waterhouse et al. (2014) found only $\sim 5,200$ profiles of vertical shear. Such small numbers of measurements cannot constrain the global distribution of turbulence.

To overcome this problem, many studies have sought to infer the strength of turbulence using observations of internal waves on vertical length scales of $\sim O(1\text{-}10)$ m (**Figure 5**; Gregg, 1989; Wijesekera et al., 1993; MacKinnon and Gregg, 2003; Polzin et al., 2014; Ijichi and Hibiya, 2015). These inferences, which are known as fine-scale parametrizations, have underpinned attempts to map the global distribution of mixing using measurements made by conductivity-temperature-depth (CTD) profilers and Argo floats (Whalen et al., 2012; Waterhouse et al., 2014; Whalen et al., 2015; Kunze, 2017). However, few studies have benchmarked the results of fine-scale parametrizations against direct measurements of turbulence (e.g., Liang et al., 2018; Takahashi and Hibiya, 2019; Takahashi and Hibiya, 2021; Fine et al., 2021).

Instruments that record structure on horizontal scales of $\gtrsim O(10)$ m offer an alternative way to both directly measure turbulence and benchmark fine-scale parametrizations (Moum, 2021). On horizontal length scales of $\lesssim 300$ m, observations reveal a regime of layered anisotropic stratified turbulence (LAST)[5] that can be straightforwardly related to the intensity of isotropic turbulence (**Figure 5**; Brethouwer et al., 2007; Klymak and Moum, 2007b; Maffioli and Davidson, 2016; Kunze, 2019). Internal-wave signals on greater horizontal length scales can be analyzed using modified fine-scale parametrizations to yield indirect estimates of the strength of turbulent mixing (e.g., Klymak and Moum, 2007a; Sheen et al., 2009; Dickinson et al., 2017).

The horizontal signals of internal waves and LAST are captured both by towed instruments and by seismic oceanography (e.g., LaFond, 1963; McKean and Ewart, 1974; Holbrook and Fer, 2005; Holbrook et al., 2013). However, seismic oceanography is distinguished by its ability to record unprecedentedly large volumes of data in short periods of time. For instance, one 175-km-long seismic image acquired over a 20-hour period shows reflective boundaries with a cumulative length of more than 5,000 km (Dickinson et al., 2017). This length is over thirty times greater than the combined length of the datasets on which Garrett and Munk (1972) based the horizontal-wavenumber description of their original semi-empirical internal-wave spectrum. Rapid acquisition also distinguishes seismic oceanography from more recent campaigns that have acquired horizontal measurements over periods of several weeks (e.g., Ferrari and Rudnick, 2000).

Spectral analysis of extensive seismic oceanographic datasets thus has the potential to provide a global catalogue of oceanic horizontal-wavenumber spectra that is unrivalled in size (cf. Polzin and Lvov, 2011). Statistical investigation of this catalogue could address questions that include:

- How accurate is the Garrett-Munk spectrum for internal waves? How do the spectral properties of internal waves vary in different oceanic environments? *See* Levine (2002), Polzin and Lvov (2011) *and* Pinkel (2020).
- What is the nature of the dynamical transition between internal waves and LAST on horizontal length scales of $\sim O(100)$ m? *See* Falder et al. (2016), Sallares et al. (2016), Kunze (2019) *and* Howland et al. (2020).
- How accurate are existing fine-scale parametrizations when applied to horizontal-wavenumber spectra[6]? Do different parametrizations work better in different oceanic environments? Is it possible to formulate new parametrizations that better apply to horizontal-wavenumber spectra? *See* MacKinnon and Gregg (2003), Klymak and Moum (2007a), Hibiya et al. (2012), Polzin et al. (2014), Waterman et al. (2014) *and* Ijichi and Hibiya (2015).

Perhaps most importantly, seismic oceanography offers a way to map the intensity of turbulent mixing in unprecedented two-dimensional detail across sections that are hundreds of kilometers in length (e.g., Tang et al., 2021; Wei et al., 2022). Advances in oceanographic instrumentation are providing new tools that can be integrated into future seismic surveys to benchmark estimates of mixing (Frajka-Williams et al., 2022). Shear probes will be mounted on Argo floats, whilst expendable profilers will measure velocity fluctuations to depths of $\sim 6,000$ m (e.g., Shroyer et al., 2016; Shang et al., 2017; Roemmich et al., 2019). Seismometers will record turbulent flow in narrow boundary layers above the ocean floor (Yang et al., 2021). Once seismic methods for estimating mixing have been accurately calibrated using these tools and using numerical simulations, existing seismic datasets will provide a way to investigate possible changes in oceanic mixing during the previous four decades, when few other measurements were available.

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[4]The term *mixing* is inconsistently used in the literature (e.g., Eckart, 1948; Muller and Garrett, 2002; Dimotakis, 2005; Naveira Garabato and Meredith, 2022). Here, we follow common convention and use the term *turbulent mixing* to describe the folding and stirring of fluid by eddying motions. By increasing the variance of temperature, salinity and density on microscales, this folding and stirring creates favorable conditions for the molecular diffusion that ultimately mixes different water masses (Moum, 2021).

[5]On length scales of $\lesssim O(1)$ m, the effects of ocean stratification are insignificant and turbulent motions have the same form in the horizontal and the vertical (Ozmidov, 1965; Dillon, 1982). This isotropic turbulence maintains a downscale transfer of energy that is exactly described by theory (Kolmogorov, 1941;

Sreenivasan, 1995). On greater length scales, the effects of stratification lead to anisotropic turbulence with a much greater horizontal than vertical extent. We follow Falder et al. (2016) in using the term *layered anisotropic stratified turbulence* (LAST) to refer to this turbulence. For further discussion see Lindborg (2006), Riley and Lindborg (2008), Riley and Lindborg (2012), Caulfield (2020) and Caulfield (2021).

[6]The accuracy of horizontal fine-scale parametrizations can be assessed by comparison to simultaneous observations of LAST in the same seismic image.

3.2 Submesoscale Currents

The submesoscale range plays host not only to internal waves, but to a menagerie of other phenomena that evolve on time scales of hours to days (**Figure 5**; Thomas et al., 2008; Callies et al., 2020). These non-internal-wave phenomena, which we collectively refer to as submesoscale currents[7] following McWilliams (2019), are thought to be vital in sustaining ecosystems and in modulating exchange of energy between mesoscale motions and microscale turbulent flows (e.g., Levy et al., 2018; Naveira Garabato et al., 2022). Unfortunately, they are difficult to discern in observational time series and in measurements made by vertically dropped instruments (McWilliams, 2016). As a result, most *in situ* observations have been obtained using platforms that sample the ocean horizontally, such as towed thermistors or ADCPs (e.g., Samelson and Paulson, 1988; Klymak and Moum, 2007a; Rocha et al., 2016; Qiu et al., 2017).

A more complete description of submesoscale currents requires rapid two- or three-dimensional sampling (McWilliams, 2019). Although gliders provide quasi-two-dimensional observations, they travel at slow horizontal speeds of ~0.3 m s^{-1} and probably only resolve features at horizontal scales greater than ~30 km (e.g., **Figure 2A**; Rudnick and Cole, 2011; Rudnick, 2016). A few field campaigns have sought three-dimensional descriptions by tracking the spread of inert tracers, by carrying out surveys with two closely spaced ships, and by combining moored, towed and dropped instruments with airborne sensors and with autonomous floats, drifters and gliders (e.g., Allen and Naveira Garabato, 2012; Shcherbina et al., 2013; Shcherbina et al., 2015; Pascual et al., 2017; Marmorino et al., 2018). However, these campaigns have small geographical extents and are limited to the upper ~ 500 m of the ocean. Satellites and airborne instrumentation have revolutionized our understanding of submesoscale activity at the sea surface (e.g., Gower et al., 1980; Munk et al., 2000; Jolliff et al., 2019; Klein et al., 2019; Martínez-Moreno et al., 2021). However, it is not well known how closely these surface motions correspond to flow at depth (e.g., Wang et al., 2010; Callies and Ferrari, 2013).

In addition to being difficult to observe, submesoscale currents are difficult to theoretically describe (e.g., McWilliams, 2010; McWilliams, 2017). As a result, developments in our understanding have been largely driven by numerical simulations (McWilliams, 2019). At present, most simulations are validated by comparison to satellite or radar observations of sea-surface height and temperature (e.g., Delandmeter et al., 2017; Schubert et al., 2019; Bashmachnikov et al., 2020; Chrysagi et al., 2021). Few studies have compared simulations to subsurface observations (e.g., Rocha et al., 2016; Liu et al., 2017; Viglione et al., 2018). Improving our ability to observe submesoscale currents and to benchmark simulations now requires an efficient way to rapidly sample thermohaline structure between the sea surface and the seafloor.

Seismic oceanography offers an unrivalled means of achieving this sampling. Unlike gliders, seismic vessels move at fast speeds of ~ 2.5–3 m s^{-1}, allowing surveys to capture submesoscale structures that evolve on time scales of hours to days. This ability can be exploited in three ways. First, seismic images can reveal the geometries and distributions of subsurface submesoscale structures in unprecedented detail. For instance, Song et al. (2011) present a seismic image which shows how submesoscale coherent vortices generate thermohaline intrusions with forms that are unanticipated by theory. By combining seismic images with inverted sections of temperature, salinity and density, Gunn et al. (2020b) show how submesoscale lenses and filaments interact with a deep-seated oceanic front. Seismic oceanography's ability to visualise submesoscale features can address questions such as:

- How abundant are submesoscale coherent vortices? How quickly do they evolve? *See* Gunn et al. (2018), Gula et al. (2019), Steinberg et al. (2019), Archer et al. (2020), McCoy et al. (2020) *and* Tang et al. (2020).
- How widespread are submesoscale fronts? To what depth do these fronts extend? How are they influenced by the presence of permanent fronts between water masses? *See* Ramachandran et al. (2014), Pascual et al. (2017), Siegelman et al. (2019), Gunn et al. (2020b) *and* Giddy et al. (2021).
- How does the size and form of imaged submesoscale structures vary with depth and with proximity to rough topography? *See* de Lavergne et al. (2016), Dauhajre et al. (2017), Ruan et al. (2017), Callies (2018) *and* Wenegrat et al. (2018).

Second, seismic oceanography can probe the statistical signatures of submesoscale currents. To date, few observational studies have resolved along-isobar and along-isopycnal hydrographic variations on submesoscale length scales, and the distribution of potential energy in the submesoscale range is poorly known (e.g., Cole and Rudnick, 2012; Callies and Ferrari, 2013; Schönau and Rudnick, 2015; Itoh and Rudnick, 2017). Improved observations will show which processes dominate transfer of energy and how they contribute to lateral stirring of water masses (e.g., Rudnick and Martin, 2002; Johnson et al., 2012; Jaeger and Mahadevan, 2018). These observations can be extracted from seismically derived sections of temperature, salinity and density (Xiao et al., 2021). As with internal waves and LAST, analysis of widespread seismic surveys can provide a catalogue of submesoscale spectra[8] that is unmatched in size. This catalogue can address questions that include:

- What are the dominant spectral slopes for temperature, salinity and spice? Are these slopes well described by theory? *See* Ferrari and Rudnick (2000), Callies and Ferrari (2013), Klymak et al. (2015), Kunze et al. (2015) *and* Erickson et al. (2020).
- At what length scale do internal waves start to dominate the spectral signal? *See* Bühler et al. (2014), Rocha et al. (2016), Qiu et al. (2017), Qiu et al., (2018), Callies (2019) *and* Thomas and Yamada (2019).
- How energetic are submesoscale currents beneath the surface mixed layer? How do currents vary with the seasons? *See* Cole et al. (2010), Callies et al. (2015), Buckingham et al. (2016), du

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[7]Our use of the term *submesocale currents* includes submesoscale coherent vortices, which are subsurface eddies with distinct hydrographic properties (McWilliams, 1985). Once formed, they can exist for several years.

Plessis et al. (2017), Siegelman et al. (2019), Yu et al. (2019), Dong et al. (2020), Erickson et al. (2020) *and* Siegelman (2020).

Finally, seismic oceanography can help calibrate satellite observations of submesoscale flow. Satellite altimetric records with near-global coverage are available for all years after 1992 (Fu et al., 1994; Callies and Wu, 2019). The resolution of these records is highly variable, and it is unclear how well they capture activity in the subsurface ocean (Wunsch, 1997). Comparison of existing seismic oceanographic datasets to historical satellite records will demonstrate the extent to which sea-surface observations can predict motions at depth (e.g., Dickinson et al., 2020; Gunn et al., 2020b; Gunn et al., 2021; Wei et al., 2022). The next generation of satellite-borne altimeters and current meters is expected to achieve resolutions as low as ~1 km (e.g., Gommenginger et al., 2019; Klein et al., 2019; Martínez-Moreno et al., 2021). Future seismic surveys could be towed along the groundtracks of these satellites, providing spatially coincident and near-contemporaneous observations of subsurface submesoscale motions. Comparison of both historical and newly acquired seismic data to satellite records could investigate questions such as:

- Can satellite observations predict the depths to which surface oceanic fronts extend? What percentage of sub-mixed-layer submesoscale eddies are observable in satellite records? *See* Gunn et al. (2020b).
- Is there a relationship between spectral power laws computed from satellite data and spectral power laws computed from submesoscale structure at depth? *See* Wang et al. (2010) *and* Callies and Ferrari (2013).
- Is there any correlation between submesoscale sea-surface motions and periods of intense turbulence at depth?

To aid calibration of satellite records, and investigation of submesocale currents more broadly, future seismic surveys could integrate novel observational tools such as swarms of autonomous robots (e.g., Jaffe et al., 2017). Autonomous tools are ideally suited to integration with seismic oceanographic surveys since they do not interfere with operation of the seismic vessel.

3.3 Abyssal Water Mass Transformations

Approximately 50% of the ocean's volume lies at depths of 2,000 m or greater (waters at these depths are referred to as the deep ocean; Roemmich et al., 2019). Much of this volume is filled by Antarctic Bottom Water (AABW) and North Atlantic Deep Water (NADW), whose circulations play a key role in

distributing heat and salt and thus in controlling global climate (Johnson, 2008; Jayne et al., 2017). Despite its importance, fewer than 10% of hydrographic measurements come from the deep ocean (de Lavergne et al., 2016). Our ability to model abyssal processes and their impacts on climate is severely constrained by this lack of data (e.g., Wunsch and Heimbach, 2014; Forget et al., 2015; Liang et al., 2015).

To date, most of our knowledge of the deep ocean has come from repeated hydrographic measurements made by ships across a globally distributed range of transects (Talley et al., 2016; Sloyan et al., 2019). Occupation of 34 of these transects over a 35-year period has yielded approximately 150 hydrographic sections that sample the deep ocean at a horizontal resolution of ~ 55 km (Desbruyères et al., 2016). In contrast, our knowledge of hydrography in the upper 2,000 m of the ocean depends on the Argo program, which since 1999 has acquired over two million hydrographic profiles using a global array that currently consists of approximately 4,000 autonomous profiling floats (Roemmich et al., 2009; Wong et al., 2020; Roemmich et al., 2022). The Deep Argo program aims to build on this success by acquiring measurements to depths of 6,000 m (e.g., Johnson and Lyman, 2014; Gasparin et al., 2020). However, it seems unlikely that a global deep Argo array will be operational before 2026 (Zilberman et al., 2019).

Seismic oceanography provides a means of extending our historical record of changes in the hydrography of the deep ocean. Although the majority of seismic reflection datasets lie above continental shelves and slopes, a significant number of surveys extend into deep near-shelf regions that are key in formation of abyssal water masses (**Figure 4**; e.g., Dickson and Brown, 1994; Orsi et al., 1999; Morozov et al., 2021). For instance, between the years 1976 and 2011 more than 360,000 km of seismic reflection transects were acquired between the shoreline of Antarctica and regions with water depths of $\gtrsim$ 5,000 m (Breitzke, 2014; note that not all of these transects are plotted in **Figure 4A**). For comparison, five repeat hydrographic transects within the Southern Ocean were occupied a cumulative total of 32 times during the same time period (Desbruyères et al., 2016). Estimation of temperature, salinity and density from seismic transects offers a way to improve the historical record of hydrographic changes and to address questions such as:

- To what extent does heaving of isopycnals in the deep ocean reflect changes in total heat content? *See* Bindoff and Mcdougall (1994), Hakkinen et al. (2016), Desbruyères et al. (2017) *and* Gunn et al. (2020a).
- How do seismic estimates of temperature change correlate to basin-wide changes estimated using acoustic thermometry? How do seismic estimates correlate to changes estimated from highly localised shipboard measurements? What do these comparisons tell us about our ability to assess temperature changes from existing datasets? *See* Munk (2006), Purkey and Johnson (2010), Purkey and Johnson, (2012), Palmer et al. (2019), Wu et al. (2020) *and* Wunsch (2020).
- How are changes in deep-ocean temperature associated with changes in abyssal turbulence, internal waves, and

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[8]Most spectral analyses of seismic oceanographic images have depended on tracking continuous seismic reflections, which usually extend along horizontal distances of $\lesssim$ 10 km (*Section 2.3.3*; **Appendix D.3**). This approach is sufficient to resolve the signals of LAST and of the high-wavenumber portion of the internal wave field. However, it does not resolve the full signal of submesoscale currents. Instead of tracking reflections, submesoscale signals could be analyzed by computing horizontal-wavenumber spectra directly from seismically estimated hydrographic sections. Aside from spectra, further statistical properties could be calculated following Klymak et al. (2015).

submesoscale currents? *See* Sheen et al. (2014), Su et al. (2018), Naveira Garabato et al. (2019) *and* Whalen et al. (2020).

To answer these questions, and to investigate turbulent mixing and submesoscale currents, use of seismic oceanography must be guided by a clear and practicable plan for its future development.

4 FUTURE DIRECTIONS

We believe that solutions to the challenges which face seismic oceanography will be best realized through collaboration amongst all researchers in the field. Key to this collaboration will be three parts:

- **Identification of priorities for the next decade of seismic oceanography.** Efficient progress will be made if researchers come together to agree upon a small number of key scientific questions that can be addressed using seismic oceanography. Detailed plans for tackling these questions can be formed. Discussion should include all researchers with an interest in the field.
- **Development of an online repository of publicly available seismic reflection datasets.** Deposited datasets should include all ancillary hydrographic data where this exists. If original seismic records cannot be shared, standardized details of acquisition, processing and data provenance should be published. Data-sharing can build on practices developed as part of observational initiatives such as the Microstructure Database, the Global Ocean Observing System, and Argo (e.g., MacKinnon et al., 2017; Tanhua et al., 2019; Roemmich et al., 2019; see microstructure.ucsd.edu and www.goosocean.org).
- **Development of an online repository of open-source computer codes**. Existing codes should be uploaded and benchmarked against hydrographically calibrated field datasets and numerical simulations. Codes that are shown to be reliable can be developed into standardized tools which will facilitate comparison of datasets. Wherever possible, codes should be automated to minimize subjective judgements. Sharing of code can build on examples such as the repository developed by the turbulent mixing community (github.com/OceanMixingCommunity).

To encourage collaboration, we have set up a Wikipedia page and code repository (en.wikipedia.org/wiki/Seismic_Oceanography and github.com/SeismicOceanographyCommunity). Anyone is welcome to contribute. Session PS06 at the 2022 American Geophysical Union Ocean Sciences meeting discussed priorities for the field, and sparked conversations that can now be taken further (see www.aslo.org/osm2022/scientificsessions/#ps).

As an example of a scientific priority, we suggest that large volumes of existing seismic data should be analyzed using automated methods for estimating the intensity of turbulent mixing (*Section 3.1*). This analysis would require development of three open-source tools:

- **Tool 1:** A standardized method for estimating temperature, salinity and density from seismic records in the absence of coincident hydrographic measurements.
- **Tool 2:** A standardized method for computing horizontal-wavenumber spectra from seismic images and for estimating diapycnal diffusivity from identified internal-wave and LAST spectral regimes.
- **Tool 3:** A standardized method for accurate numerical modeling of seismic reflection profiling of time-variant thermohaline structure.

Tools 1 and **2** would include rigorous assessment of uncertainties in estimated quantities. Together, these two components would form a toolkit for rapid, comparable estimation of diapycnal diffusivity and of the form of the internal wave field at disparate locations. Seismic-derived estimates of temperature, salinity and density would free this analysis from dependence upon independent hydrographic data. Accuracy would be tested using the numerical modeling package developed as **Tool 3**. The unprecedented number of observations of turbulent mixing could be combined with machine-learning techniques to inform improved climate models (Zanna and Bolton, 2021).

Other researchers will no doubt disagree with our suggested priority and have suggestions of their own. We hope that this article will provoke discussion about the best way to proceed, and will lead to development of shared resources and projects. Similar collaborative development is fuelling formation of a new generation of observational tools, including satellite-borne wide-swath altimeters, moored temperature microstructure recorders, autonomous floating seismometers, saildrones and ultra-wideband underwater communication (Fu and Ferrari, 2008; Moum and Nash, 2009; Hello et al., 2011; Cross et al., 2015; Ghaffarivardavagh et al., 2020). It is time for seismic oceanography to join their ranks.

DATA AVAILABILITY STATEMENT

The Supplementary Material - including all appendices, all tables, and sources of data for Figure 4 - can be found online at www.frontiersin.org/articles/10.3389/fmars.2022.736693/full#supplementary-material. Additional supporting information, including editable versions of all figures and tables, is available at doi.org/10.6084/m9.figshare.c.5984767. A repository for future sharing of code and data has been set up at github.com/SeismicOceanographyCommunity.

AUTHOR CONTRIBUTIONS

AD conceived the article, reviewed the literature and drafted the text with advice from KLG. Both authors contributed equally to development of the figures. KLG set up the Wikipedia page and GitHub repository with feedback from AD. Both authors contributed to the article and approved the submitted version.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.736693/full#supplementary-material

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