Exploring the Ocean Through Soundscapes

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Listening to underwater soundscapes helps us understand how ocean physics and the biology of marine communities are responding to a dynamically changing ocean.

It is a clear afternoon, and you are looking out at the skyline from the highest point within 100 km. From this vantage point, you can see for "miles and miles," but the only sounds you can hear are the people with you, a few birds, insects, and the wind. Now, if you went to an equivalent point in the ocean to stand on the mid-Atlantic ridge overlooking the ocean's abyssal plain, you would still have 1,200 m of inky black water above and around you. Listening through a hydrophone, the sounds you hear would be extraordinarily rich. Crustaceans would be heard scratching at the rock and deepwater corals. Sperm, beaked, and pilot whales would be searching for food using echolocating click trains. Blue and fin whale calls, trapped in the deep sound channel, would arrive from thousands of kilometers away. Every few seconds, the sound channel would also bring you energy pulses from oil and gas seismic surveys arriving from Brazil, Africa, the North Sea, and Newfoundland.

Underwater acoustic research has revealed the amazing physics of how sound propagates in the ocean, primarily motivated by using sound to detect oil and gas under the Earth's crust or for naval applications. Along the way, we learned that marine life has capitalized on ocean physics and evolved the use of sound as a primary sensory modality for interacting with the environment. We are now listening in on the underwater conversations and using passive acoustics to assess marine biodiversity, animal density, and ecosystem status and health. This article introduces the idea of an underwater soundscape, successes in using the soundscape to understand marine ecology, the modeling of soundscapes, and ocean sound as an essential ocean variable (EOV).

Underwater Soundscapes

A great deal of information related to ocean dynamics and human activities can be gained simply by listening to the ambient-sound field. This acoustic landscape, or soundscape, is the sum of multiple sound sources that all arrive at the location of a receiving animal or acoustic recorder. The sounds measured at an acoustic recorder are characterized by our typical engineering measurements such as sound pressure levels, weighted sound exposure levels (SELs), roughness, and kurtosis. The percept of sounds to marine life depends on the relative contribution of each source, source direction, propagation through the environment, behavioral context, hearing capabilities of the listener, and history of the listener with similar sounds (**Figure 1**).

Underwater soundscapes are dynamic; they vary in space and time and within and between habitats. Sound in the deep ocean propagates such great distances underwater that soundscapes are influenced not only by local conditions but also by much more distant sound sources than in air. The underwater soundscape is

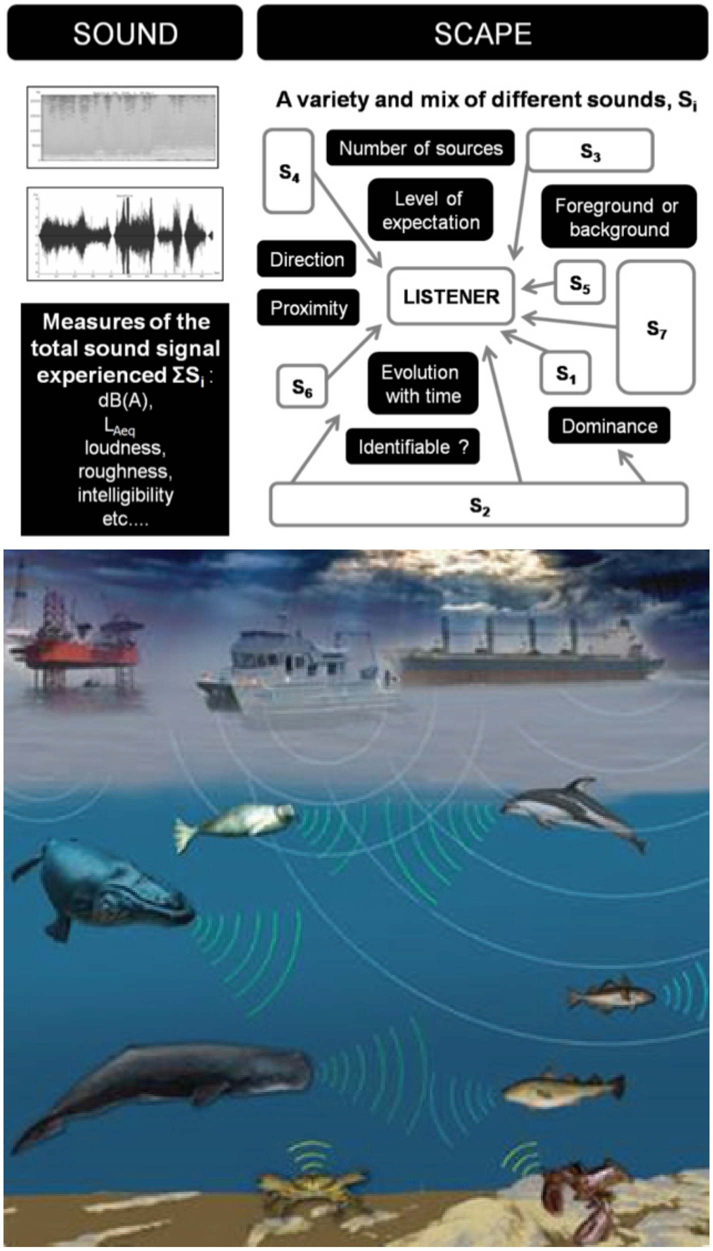

Figure 1. Top: *soundscape is composed of "sound," the physical measurements of the sound field, and the "scape" that conveys how all of the sound sources overlap and are perceived by the listener* ***White boxes with*** $S_{i(1\text{-}7)}$*, signals from sound sources in the environment with different sizes and orientations meant to convey different source types;* ***black boxes,*** *physical and perceptual characteristics of the sound signals by the listener.* L_{Aeq}*, sound level in decibels equivalent to the total A-weighted sound energy measured over a stated period of time. From Jennings and Cain (2013).* ***Bottom:*** *graphic representation of the multiple ocean sources contributing to an ocean soundscape. From NOAA's Ocean Noise Strategy. Available at http://acousticstoday.org/nefsc.*

composed of contributions (**Figure 2**) from human activity (e.g., shipping, fishing vessels, seismic airgun surveys), natural abiotic or geophysical processes (e.g., wind, rain, ice), and acoustic contributions from biological sources (e.g., sound produced from animal movement and vocalizations from marine mammals, fishes, and invertebrates). In **Figure 2**, the ***single-headed arrows*** show that the soundscape is directly influenced in a single direction by anthropogenic and abiotic factors and the ***double-headed arrows*** indicate that the soundscape is not only influenced by but also influences the biological soundscape component. Consequently, the underwater soundscape is not merely a physical parameter of the environment to be measured and quantified. The soundscape depends on the listener and has a feedback loop where changes in the soundscape have the potential to impact acoustic behavior and biotic factors that influence the behavioral ecology of the ecosystem and ultimately further alter the soundscape (**Figure 2**).

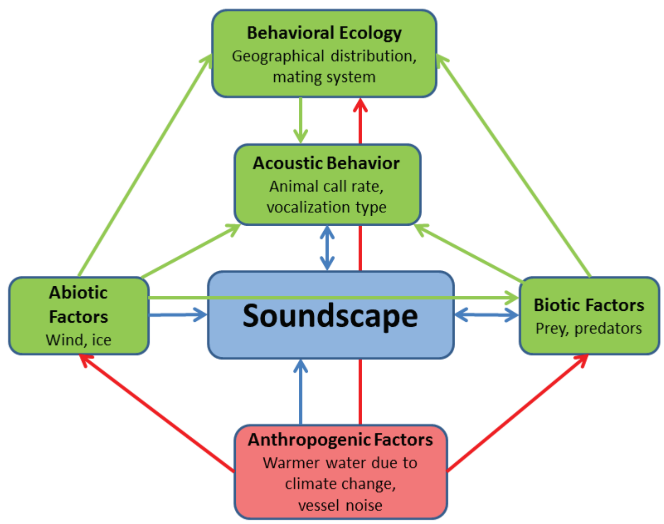

Figure 2. *Soundscape presented within the context of acoustic ecology.* ***Green boxes and arrows****, natural factors: behavioral ecology, acoustic behavior, and abiotic and biotic factors contributing to (****outgoing arrows****) or impacted by (****incoming arrows****) the soundscape (****blue box and arrows****);* ***red box and arrows,*** *interactions and influences of human activity related to or impacting the soundscape. Adapted from van Opzeeland and Miksis-Olds (2012, Figure 1).*

Soundscape analysis is performed on live-data streams or recordings of received pressure signals from passive acoustic recorders deployed on the ocean bottom or moored in the water column. The recordings allow us to observe marine habitats without the confounding effects of human presence or sampling biases. Recordings of the full range of ocean sounds have a wide bandwidth (150 kHz or more), last for periods of months to years, and often are collected at multiple locations that the researchers compare for similarities and differences (listen to real-time soundscapes recorded in different ocean locations at http://www.listentothedeep.com). These datasets are called five-dimensional because they have

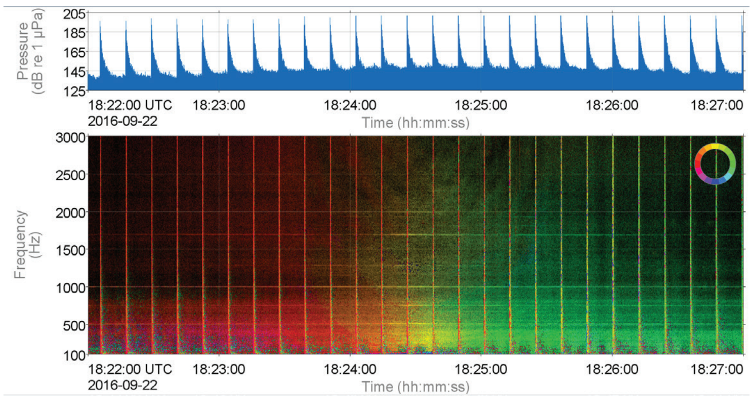

Figure 3. Five minutes of acoustic data from a seismic vessel and airgun array passing over a directional hydrophone. ***Top:*** *sound pressure level time series.* ***Bottom:*** *spectrogram where color indicates direction of arrival shown by the color wheel (****yellow****, North;* ***blue****, South). The sensor was 60 cm from the seabed in 110 m of water. Note that the vessel direction color changes before the impulses from the airgun array because the array was ~100 m behind the vessel.*

time, frequency, amplitude, latitude, and longitude. The goal of soundscape analysis is extracting information from the recordings to identify which sources are present, the source amplitudes, how sources interact, and how animals in the environment may perceive and respond to the sounds. In recent years, some research teams have started making directional soundscape recordings that increase the data to six dimensions by adding the direction of arrival (**Figure 3**). Directional pressure sensors in deep water also offer the potential to measure particle motion. Unfortunately, this methodology does not extend to accurate measurements of particle motion near the sea surface, at the seabed, or in shallow water because it is not linearly related to pressure in these regions. Particle motion, as opposed to pressure, is the component of sound sensed by most fishes and marine invertebrates. Its measurement and perception is a subject that needs extensive investigation (Hawkins and Popper, 2017).

Passive acoustic monitoring (soundscape) data can be selectively broken down to gain a greater understanding of the sources shaping the temporal, spatial, and spectral patterns of the acoustic environment (Mann, 2012; Au and Lammers, 2016; e.g., **Figure 4**). There are a wide variety of acoustic measures and presentation formats in the marine soundscape literature related to the foci of each study. For example, studies of soundscape patterns and trends tend to utilize measures of sound pressure levels (**Figure 4, A** and **B**) and sound level exceedance percentiles (sound level that is exceeded *N*% of the time during a specified time period; **Figure 4D**), whereas studies of ecosystem biodiversity derive acoustic diversity indices from the soundscape repre-

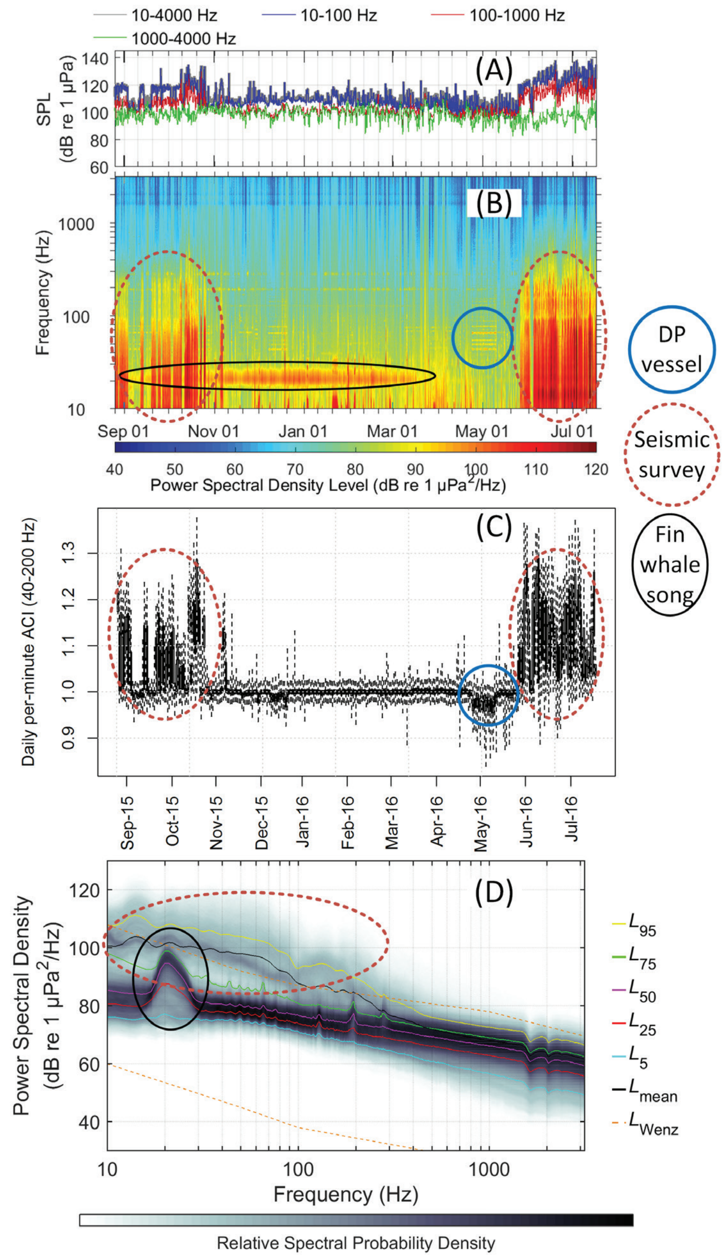

Figure 4. *Examples of soundscape data presentations using an 11-month dataset recorded 20 m off the seabed in 1,280 m of water off Newfoundland, Canada.* ***A:*** *time series of 1-hour band-limited sound pressure levels (SPL).* ***B:*** *long-term spectral average of the complete dataset.* ***C:*** *daily distributions of 1-minute acoustic complexity index (ACI) values for the frequency band of 40-200 Hz. Values below 1 indicate lower complexity (i.e., continuous sound sources) and values above 1 indicate higher complexity (impulsive sound sources).* ***D:*** *distribution of 1-minute power spectral densities including exceedance percentiles (i.e., 5% of the power spectral density values exceeded the L5 line).* ***Orange dashed ellipses,*** *presence of seismic survey signals;* ***black solid ellipses,*** *fin whales;* ***solid blue circles,*** *a distant dynamic positioning (DP) vessel signature.*

sentative of the number of vocal species present in an area (**Figure 4C**). Soundscape analyses have provided a means for better understanding the influences of environmental parameters such as sea ice presence and lunar cycles on local acoustic processes (Miksis-Olds et al., 2013a; Staaterman et al., 2014), assessing habitat quality and health on coral reefs (McWilliam and Hawkins, 2013; Staaterman et al., 2014), measuring biodiversity (Parks et al., 2014; Harris et al., 2016), and for better understanding the impacts and risks of human contributions to the soundscape have on marine life.

Utilization of Underwater Soundscapes

Over the past decade, the costs of collecting and analyzing passive acoustic-monitoring data have been steadily decreasing, leading to an increasing number of studies that explore how animals use information from their environmental soundscape for communication, orientation, and navigation (Slabbekoorn and Bouton, 2008; Pijanowski et al., 2011; also see article by Slabekoorn in this issue of *Acoustics Today*). The concept of using ambient or reflected sounds (as opposed to specific communication signals) as cues to direct movement or identify appropriate habitats has recently been identified as a new field of study referred to as *soundscape orientation*, and the concept is also included within the broader field of *soundscape ecology* in the scientific literature (Slabbekoorn and Bouton, 2008; Pijanowski et al., 2011). It has been speculated that large baleen whales use ambient acoustic cues or acoustic landmarks to guide their migration (Able, 1980; Kenney et al., 2001). Similarly, it has been proposed that soundscape cues could provide ice seals in the water, a salient acoustic gradient between open water and solid ice conditions by which the seals can orient to maintain access to open water for breathing (Miksis-Olds and Madden, 2014).

Laboratory and field studies have demonstrated that both invertebrates and fishes use soundscape cues for orientation and localization of appropriate settlement habitat. Stanley et al. (2011) measured the sound intensity level required to elicit settlement and metamorphosis in several species of crab larvae, and Simpson et al. (2008) showed that coral reef fish seem to respond more strongly to the higher frequency components (>570 Hz) of the reef soundscape. Habitats with greater biodiversity are often associated with richer acoustic soundscapes compared to low-diversity habitats, which in itself may be an important cue for animal orientation in water and air (Sueur et al., 2008; Pijanowski et al., 2011; Stanley et al., 2012).

An example of the utility of long-term soundscape analysis is the survey of low-frequency underwater ocean sound over the past 50 years off the West Coast of the United States. Using a combination of declassified US Navy recordings and scientific datasets, a steady increase in low-frequency sound (10-200 Hz) has been documented and mainly attributed to an increase in commercial shipping (Ross, 2005). Sound levels have increased at approximately 3 dB/decade (0.55 dB/year) up until the 1980s (McDonald et al., 2006) and then slowed to 0.2 dB/year (Chapman and Price, 2011). The most recent measurements in this region show a leveling or slight decrease in the sound levels since the late 1990s despite increases in the number and size of ships (Andrew et al., 2011).

Blue, fin, sei, Brydes, right, and humpback whales all communicate in the 10- to 200-Hz frequency band; infrasound from waves crashing onshore (that marine animals likely use for orientation) is also in this band. Understanding how marine life uses this frequency band and the effects of human contributions in this same frequency band is the subject of many soundscape studies. Shipping increases alone do not fully account for the observed 10- to 12-dB increase in the 20- to 40-Hz band from 1965 to 2003 (Ross, 1993, 2005). Activities from oil and gas exploration and production as well as from renewable energy sources have also increased the total sound levels in this band (Boyd et al., 2011). Biotic sound levels have likely also increased due to recovering whale populations and the "Lombard effect," which is the increase in call amplitude to compensate for higher noise levels. The Lombard effect has been demonstrated in humans and many animal populations and may contribute to rising low-frequency levels as animals vocalize louder to be heard above the noise (Tyack, 2008).

Climate change is increasing the amount of glacial ice entering the oceans, and as glaciers disintegrate, they generate low-frequency noise with large source levels that contributes to the regional noise budget for extended periods (Dziak et al., 2013). The regional limits of soundscapes, even for low frequencies that propagate long distances, is underscored by the differences in long-term sound level increases. Although studies have reported a significant increase in ambient-noise levels in the North Pacific, current studies in the Indian, South Atlantic, and equatorial Pacific Oceans have not observed a uniform increase in ocean sound levels (Miksis-Olds et al., 2013b; Miksis-Olds and Nichols, 2016). Very little is known about the global soundscape as a whole, and this is an active area of ocean exploration. Theory and observations suggest that human-generated noise could be approaching levels at which negative effects on marine life may be occurring (Boyd et al., 2011).

Soundscape Modeling

Thus far we have discussed decomposing the sounds measured at points in the ocean to explore what sources are present and how they shape the acoustic space used by humans and marine life (**Figure 1**). However, it is also possible to estimate a soundscape by combining the acoustic signatures of regional sources. Soundscape modeling is the process of composing the sounds at a receiver based on assumed sources, source locations, movements, and acoustic propagation conditions. Researchers will model soundscapes to test detection, classification, and localization algorithms in controlled conditions or to predict the potential effects of human activities. Simplifying assumptions have traditionally been made to reduce the computational burden, especially for the sea surface noise from wind and waves and the acoustic propagation loss. As computer speeds increase, more advanced sound source and propagation models enable increasingly rapid algorithm development and improved understanding of sound propagation, and provide better information for decision makers during the evaluation of permit applications requesting the approval for incidental exposure to marine life during industrial, scientific, or military activities (Aulanier et al., 2017; e.g., **Figure 5**).

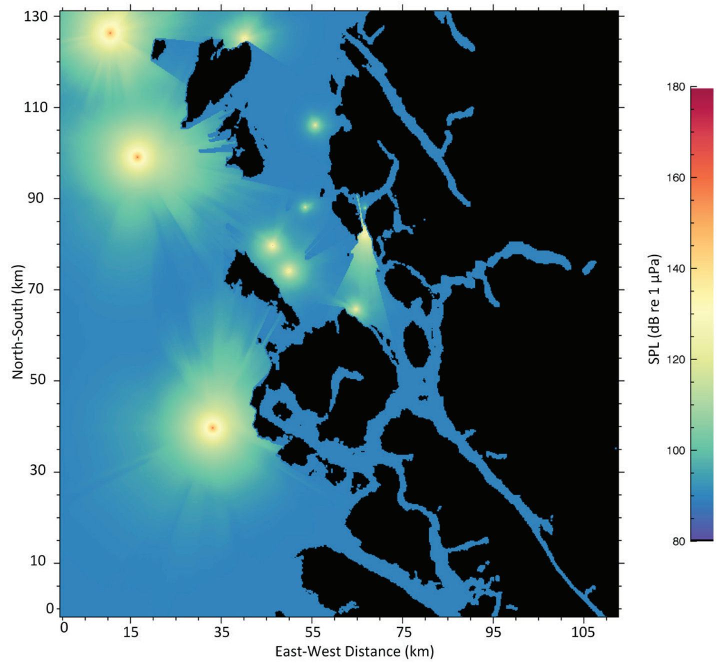

Figure 5. *Modeled SPL from a snapshot of automated identification system vessel locations, which was generated as part of research into the cumulative effects of current and additional projected vessel traffic at the port of Prince Rupert, British Columbia, Canada. Figure provided by JASCO Applied Sciences, Nova Scotia, Canada, and the Prince Rupert Port Authority.*

Acoustic Measurements for Conservation

Understanding the effects of noise on marine life motivates many marine soundscape measurements. The effects of noise are often grouped into four categories: (1) death and injury, (2) physiological effects, (3) behavioral disturbance, and (4) masking of sounds. Protecting marine life from death and injury has been the focus of recent industry and government funding. As a result, we know more about what sounds levels and metrics predict injury, especially to marine mammals, than those associated with behavioral changes and masking. Two threshold measurements are used to estimate the onset of injury in marine life. The peak sound pressure level of the impulse (e.g., explosion, pile-driving strike) is used to assess the possibility of physiological damage to tissues (e.g., barotrauma in fishes). The amount of sound energy that can damage hearing in marine life is estimated by the SEL, which accumulates sound energy over time (Popper et al., 2014; National Marine Fisheries Service, 2016). The SEL in the marine environment is a complicated dynamic related to the source distance, acoustic propagation conditions, and the overlap between the frequency content of the source and the hearing sensitivity of the receiving animals. For human sound exposure, we use the familiar A-weighting, and similar weighting functions are proposed for five groups of marine mammals (Southall et al., 2007). We do not yet understand the hearing of fishes, sea turtles, and invertebrates sufficiently to propose weighting functions for these groups.

Studies of behavioral disturbance and auditory masking are increasing now that the acute effects of noise are better understood. These studies are directly associated with the concept of a soundscape; how does the marine life interpret and react to sound? Most studies of behavioral disruption relate the reaction to the sound pressure level at the time of the reaction. Much additional work is required to better understand what measurements, including particle motion, are appropriate for understanding behavioral disruption on most taxa. Masking occurs when the ability to detect or recognize a sound of interest is degraded by the presence of another sound, the masker (Dooling et al., 2015). Underwater signals can be masked by natural components of the soundscape such as sea ice, wind-wave interactions, rain, and distant animal choruses or vocal bouts as well as by anthropogenic activities. Whereas studies of sound-induced injury or behavioral disruption focus just on the signal of interest, studies on masking must quantify ambient noise to estimate the signal-to-noise ratio, which is critical for estimating when an animal can detect a signal.

Standardizing Marine Soundscape Measurements

The application of soundscape measurements in studies assessing the effects of human sound, mapping the distribution of soniferous marine life, and understanding the role of sound in the ecology of marine life is growing and is contributing to a much larger community engaged in the passive acoustic-monitoring and soundscape analysis. As a result, the community has identified a need to develop standard terminology and methods that help ensure that research and compliance measurements are repeatable and comparable across projects. International Organization for Standardization (ISO) Standard 18405 on *Underwater Acoustics – Terminology* (ISO, 2017) includes a definition of an underwater soundscape for the first time.

Underwater Acoustics:
characterization of the *ambient sound* in terms of its spatial, temporal, and frequency attributes and the types of sources contributing to the sound field.

Ambient sound is the sound field measured in the absence of the noise related to the measuring system. The concept of a soundscape has its roots in understanding how humans interpret the urban sound environment. The underwater acoustics definition does not include elements of perception because we cannot know conclusively how marine life interprets the sounds. The ISO Standard 18405 goes on to provide precise definitions of underwater acoustic terminology that will help groups exchange results using a common notation.

The ISO Standard 18405 terminology does not define how to describe a soundscape. Given the wide range of metrics and indices that may be used to describe a soundscape and the uncertainty surrounding the effects and perception of noise, arriving at consensus among researchers will take time. The Atlantic Deepwater Ecosystem Observation Network (ADEON; https://adeon.unh.edu/) team developed three project standards, based on the ISO Standard 18405 terminology, that define the baseline metrics, data collection, and data-processing methods that the project will use for measuring and documenting the soundscape. The project team hopes that the documents (available on the project website) will start a discussion that leads to a consensus on the minimum description of an underwater soundscape, likely through a new working group within ISO Technical Committee 43.

Ocean Sound: An Essential Ocean Variable

Expanding efforts to measure ocean soundscapes align well with the increased focus on ocean observing systems. The Global Ocean Observing System (GOOS) was developed by the Intergovernmental Oceanographic Commission of UNESCO around three critical themes to gain a better understanding of ocean climate, ecosystems, and human impacts and vulnerabilities: (1) climate, (2) ocean health, and (3) real-time services (www.goosocean.org). The coordinated, long-term system of ocean observatories is built on a framework designed to be flexible, adapt to scientific innovation, address societal needs, and deliver an observation system with a maximum user base and societal impact. The GOOS framework relates all ocean observations to EOVs to ensure measurements cut across observation platforms and represent the most cost-effective plan to provide optimal global coverage for each EOV. The GOOS expert panels consider EOVs in terms of scientific readiness level, societal relevance, and feasibility.

The diverse applications for information gained from listening to the ocean inspired the International Quiet Ocean Experiment Program (www.IQOE.org) to propose Ocean Sound as an EOV to the GOOS Biology and Ecosystems Panel for inclusion in the GOOS network. Although ocean sound is a physical measurement characteristic of the marine environment, the Biology and Ecosystems Panel was deemed the most appropriate for submission because the majority of the ocean sound products derived from its measurement have direct or indirect biological and ecosystem applications related to the economy, food, conservation, weather, and sustainability (**Table 1**). Ocean Sound addresses 7 of the 10 GOOS societal pressures and all nine of the GOOS societal drivers (**Table 1**). The observational scale of ocean sound networks and recording platforms will allow for the study of phenomena ranging in scale from single acoustic events to long-term trends in ambient sound (**Figure 6**). The Ocean Sound EOV will forge major advances in our understanding of ocean soundscapes, the effects it has on marine life, and how acoustic monitoring can be used to assess biodiversity and ecosystem health.

***Table 1.** Ocean Sound essential ocean variable information*

Subvariables	Sound pressure and Particle motion
Derived products	Sound field and trends, Sound pressure levels, Spectrum levels, Band levels (e.g., octave band), Soundscape, Source levels, and Biodiversity indicators
Supporting variables	Sources: Distribution and characteristics of anthropogenic, abiotic, and biotic sources Propagation parameters: Sound speed profiles; Ocean currents and other physical oceanographic phenomena; Boundary conditions (e.g., sea surface roughness, sea ice characteristics [e.g., roughness and thickness], and seafloor [bathymetry, geoacoustic properties]) Receivers: Hydrophone sensitivity as a function of frequency and directionality of the receiving system
Societal drivers	(1) Need for scientific knowledge and data access, (2) Sustainable economic growth and development, (3) Conservation of biodiversity and ecosystems, (4) Sustainable use of biodiversity and resources in general, (5) Environmental quality and health, (6) Capacity building and technology transfer, (7) Food security, (8) Threat prevention and impact mitigation, and (9) To improve management through an integrated ecosystem approach
Societal pressures	(1) Climate change, (2) Ocean acidification, (3) Extreme weather events, (4) Loss of resources (habitats and biodiversity), (6) Mining, (9) Noise, and (10) Coastal development

Future Outlook

There has been a substantial amount of progress in the study and application of underwater soundscapes in the past decade, but there is still a significant gap in applying the perceptual construct of underwater soundscapes to marine life in terms of masking and sense of community space as reflected in the human soundscape literature. The challenge of integrating the perception into underwater soundscape applications mirrors that of terrestrial soundscape colleagues who are grappling with soundscape perception in wildlife. We will likely never understand perception across all of the animal taxa to fully identify and quantify their experience of the underwater and terrestrial soundscapes. A tractable step forward will be to better understand the hearing capabilities and variability across individuals and species and in terms of context linked to age, gender, previous noise exposure, and behavioral state. This is a lofty endeavor because there are diverse sound detection organs employed underwater, e.g., mammalian ears similar to ours, otolith organs in fish, and statocyst organs in invertebrates. This knowledge is critical to appropriately weighting soundscapes of different animal groups to assess effects related to sound exposures or the changing acoustic environment.

It is also important to make clear that this article does not directly address the particle motion component of sound in the soundscape. We recognize, however, that this is an incredibly important component of the soundscape for a

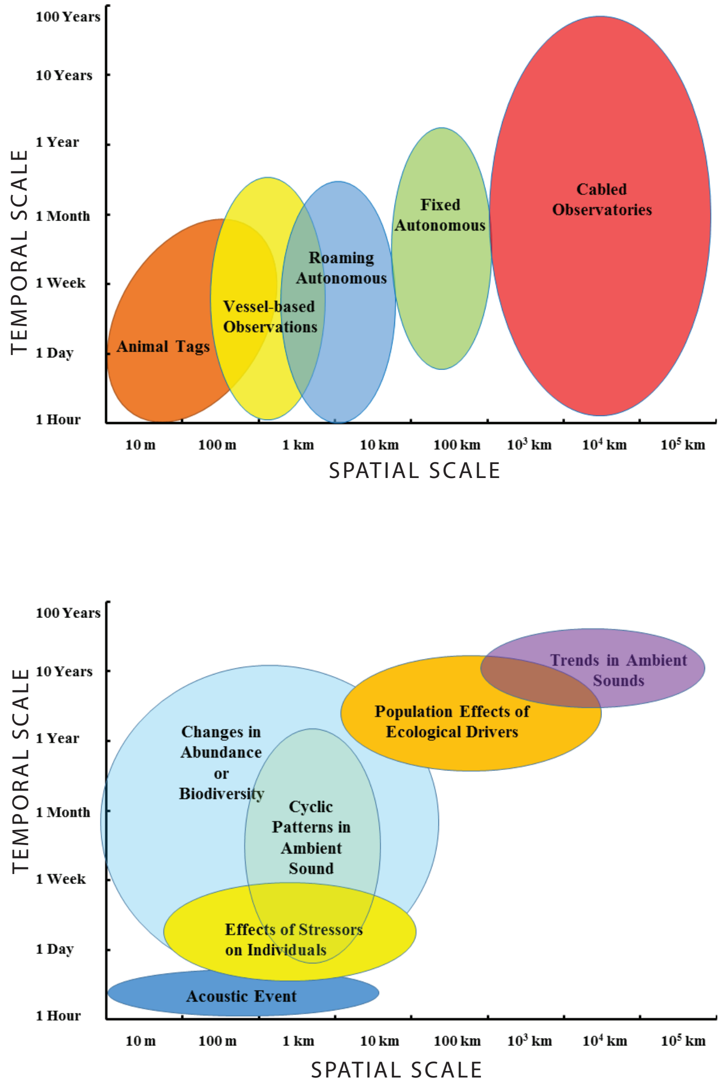

***Figure 6. Top:** observational scales of Ocean Sounds essential ocean variable (EOV) recording platforms. Passive-recording sensors range in size and recording capabilities from small, short deployment tags attached directly to animals to freely drifting autonomous sensors of intermediate capability to large-scale observatories with sensors cabled directly to the shore for long-term recording capabilities. **Bottom:** acoustic phenomena to be captured by the Ocean Sound EOV range in scale from single acoustic detections of a passing ship or underwater earthquakes to long-term trends in ambient ocean sound over decades. Ocean Sound supports the derivation of metrics and acoustic indices estimating ecosystem biodiversity, the abundance of singing whales, and the effects of environmental change at the individual and population level.*

majority of marine taxa (e.g., fish, invertebrates) that sense this component of sound (Hawkins and Popper, 2017). This gap exists because historically instrumentation to measure particle motion in the open ocean has not been readily accessible to the research community. As new technology becomes available to measure this parameter of the sound field underwater, we expect exciting advances in underwater soundscape insight and applications.

The final and arguably the most important open challenge associated with ocean soundscapes is how best to comprehend acoustic measurements and models in six dimensions. The interdisciplinary nature of soundscape research must again expand to embrace computer scientists, cognitive psychologists, and internet technology experts to advance the perception of underwater soundscapes beyond the compartmentalized visual imaging of single- or two-dimensional soundscape images to encompass innovative combinations of visual and auditory representation to fully capture the soundscape complexity in a way we can best perceive.

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References

Able, K. P. (1980). Mechanisms of orientation, navigation, and homing. In Gauthreaux, S. A., Jr. (Ed.), *Animal Migration, Orientation, and Navigation*. Academic Press, New York, pp. 283-373.

Andrew, R. K., Howe, B. M., and Mercer, J. A. (2011). Long-time trends in ship traffic noise for four sites off the North American West Coast. *The Journal of the Acoustical Society of America* 129, 642-651.

Au, W. W. L., and Lammers, M. O. (Eds). (2016). *Listening in the Ocean*. Springer-Verlag, New York.

Aulanier, F., Simard, Y., Roy, N., Gervaise, C., and Bandet, M. (2017). Effects of shipping on marine acoustic habitats in Canadian Arctic estimated via probabilistic modeling and mapping. *Marine Pollution Bulletin* 125(1-2), 115-131.

Boyd, I. L., Frisk, G., Urban, E., Tyack, P., Ausubel, J., Seeyave, S., Cato, D., Southall, B., Weise, M., Andrew, R., Akamatsu, T., Dekeling, R., Erbe, C., Farmer, D., Gentry, R., Gross, T., Hawkins, A., Li, F., Metcalf, K., Miller, J. H., Moretti, D., Rodrigo, C., and Shinke, T. (2011). An International Quiet Ocean Experiment. *Oceanography* 24, 174-181.

Chapman, N. R., and Price, A. (2011). Low frequency deep ocean ambient noise trend in the Northeast Pacific Ocean. *The Journal of the Acoustical Society of America* 129, EL161-EL165.

Dooling, R. J., Leek, M. R., and Popper, A. N. (2015). Effects of noise on fishes: What we can learn from humans and birds. *Integrative Zoology* 10, 29-37.

Dziak, R., Fowler, M. J., Matsumoto, H., Bohnenstiehl, D. R., Park, M., Warren, K., and Lee, W. S. (2013). Life and death sounds of iceberg A53a. *Oceanography* 26, 10-12.

Harris, S. A., Shears, N. T., and Radford, C. A. (2016). Ecoacoustic indices as proxies for biodiversity on temperate reefs. *Methods in Ecology and Evolution* 7, 713-724.

Hawkins, A. D., and Popper, A. N. (2017). A sound approach to assessing the impact of underwater noise on marine fishes and invertebrates. *ICES Journal of Marine Science* 74, 635-651.

International Organization for Standardization (ISO). (2017). *Underwater Acoustics—Terminology*. Standard ISO/DIS 18405.2:2017, prepared by Technical Committee ISO/TC 43, Acoustics, Subcommittee SC 3, *Underwater Acoustics*, ISO, Geneva, Switzerland. Available at https://www.iso.org/standard/62406.html. Accessed October 16, 2017.

Jennings, P., and Cain, R. (2013). A framework for improving urban soundscapes. *Applied Acoustics* 74(2), 293-299.

Kenney, R. D., Mayo, C. A., and Winn, H. E. (2001). Migration and foraging strategies at varying spatial scales in western North Atlantic right whales: A review of hypothesis. *Journal of Cetacean Research Management* 2, 251-260.

Mann, D. A. (2012). Remote sensing of fish using passive acoustic monitoring. *Acoustics Today* 8(3), 8-15.

McDonald, M. A., Hildebrand, J. A., and Wiggins, S. M. (2006). Increases in deep ocean ambient noise in the Northwest Pacific west of San Nicolas Island, California. *The Journal of the Acoustical Society of America* 120, 711-717.

McWilliam, J. N., and Hawkins, A. D. (2013). A comparison of inshore marine soundscapes. *Journal of Experimental Marine Biology and Ecology* 446, 166-176.

Miksis-Olds, J. L., Bradley, D. L., and Niu, X. M. (2013b). Decadal trends in Indian Ocean ambient sound. *The Journal of the Acoustical Society of America* 134, 3464-3475.

Miksis-Olds, J. L., and Madden, L. E. (2014). Environmental predictors of ice seal presence in the Bering Sea. *PLoS ONE* 9, e106998.

Miksis-Olds, J. L., and Nichols, S. M. (2016). Is low frequency ocean sound increasing globally? *The Journal of the Acoustical Society of America* 139, 501-511.

Miksis-Olds, J. L., Stabeno, P. J., Napp, J. M., Pinchuk, A. I., Nystuen, J. A., Warren, J. D., and Denes, S. L. (2013a). Ecosystem response to a temporary sea ice retreat in the Bering Sea. *Progress in Oceanography* 111, 38-51.

National Marine Fisheries Service (NMFS). (2016). *Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts*. NOAA Technical Memorandum NMFS-OPR-55, NOAA, US Department of Commerce, Silver Spring, MD. Available at http://acousticstoday.org/noaaagt. Accessed October 16, 2017.

Parks, S. E., Miksis-Olds, J. L., and Denes, S. L. (2014). Assessing marine ecosystem acoustic diversity across ocean basins. *Ecological Informatics* 21, 81-88.

Pijanowski, B. C., Villanueva-Rivera, L. J., Dumyahn, S. L., Farina, A., Krause, B. L., Napoletano, B. M., Gage, S. H., and Pieretti, N. (2011). Soundscape ecology: The science of sound in the landscape. *BioScience* 61, 203-216.

Popper, A. N., Hawkins, A. D., Fay, R. R., Mann, D. A., Bartol, S., Carlson, T. J., Coombs, S., Ellison, W. T., Gentry, R. L., Halvorsen, M. B., Lokkeborg, S., Rogers, P., Southall, B. L., Zeddies, D. G., and Tavolga, W. N. (2014). *ASA S3/SC1.4 TR-2014 Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report Prepared by ANSI-Accredited Standards Committee S3/SC1 and Registered with ANSI*. Springer International Publishing, Cham, Switzerland.

Ross, D. (1993). On ocean underwater ambient noise. *Acoustic Bulletin* 18, 5-8.

Ross, D. (2005). Ship sources of ambient noise. *IEEE Journal of Ocean Engineering* 30, 257-261.

Simpson, S. D., Meekan, M. G., Jeffs, A., Montgomery, J. C., and McCauley, R. D. (2008). Settlement-stage coral reef fish prefer the higher-frequency invertebrate-generated audible component of reef noise. *Animal Behaviour* 75, 1861-1868.

Slabbekoorn, H., and Bouton, N. (2008). Soundscape orientation: A new field in need of sound investigation. *Animal Behaviour* 76, e5-e8.

Southall, B. L., Bowles, A. E., Ellison, W. T., Finneran, J. J., Gentry, R. L., Greene, C. R., Jr., Kastak, D., Ketten, D. R., Miller, J. H., Nachtigall, P. E., and Richardson, W. J. (2007). Marine mammal noise exposure criteria: Initial scientific recommendations. *Aquatic Mammals* 33(4), 411-521.

Staaterman, E., Paris, C. B., DeFerrari, H. A., Mann, D. A., Rice, A. N., and D'Alessandro, E. K. (2014). Celestial patterns in marine soundscapes. *Marine Ecology Progress Series* 508, 17-32.

Stanley, J. A., Radford, C. A., and Jeffs, A. G. (2011). Behavioural response thresholds in New Zealand crab megalopae to ambient underwater sound. *PLoS ONE* 6, e28572.

Stanley, J. A., Radford, C. A., and Jeffs, A. G. (2012). Location, location, location: Finding a suitable home among the noise. *Proceedings of the Royal Society of London B: Biological Sciences* 270, 3622-3631.

Sueur, J., Pavoine, S., Hamerlynck, O., and Duvail, S. (2008). Rapid acoustic survey for biodiversity appraisal. *PLoS ONE* 3, e4065.

Tyack, P. L. (2008). Implications for marine mammals of large-scale changes in the marine acoustic environment. *Journal of Mammalogy* 89, 549-558.

van Opzeeland, I. C., and Miksis-Olds, J. L. (2012). Acoustic ecology of pinnipeds in polar habitats. In Eder, D. L. (Ed.), *Aquatic Animals: Biology, Habitats, and Threats*. Nova Science Publishers, Inc., New York, pp. 1-52.

BioSketches

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Bruce Martin (JASCO Applied Sciences, Dartmouth, Canada) has been working in acoustic data collection and analysis since 1991. From 1991 to 2007, he was involved with the development of combined active-passive sonars. In 2007, Bruce switched to environmental acoustics and soundscapes. He has worked on numerous projects including the Chukchi Sea acoustic monitoring project (2007-2014), Tappan Zee pile-driving acoustic monitoring projects (2010-2014), and a wide-area monitoring program on Canada's East Coast (2015-2018). Bruce is pursuing a PhD at Dalhousie University, Halifax, Canada, where his research interest is in soundscape ecology, especially automated techniques for quantifying sources in the soundscape.

Peter Tyack is a professor of marine mammal biology at the University of St Andrews, Scotland. His research focuses on behavioral ecology, acoustic communication, and social behavior in marine mammals. He has studied reproductive advertisement in baleen whales, individually distinctive contact calls, and echolocation in deep-diving toothed whales. He has developed new methods to sample behavior continuously from marine mammals, including the development of sound-and-orientation recording tags. He has developed a series of studies on responses to anthropogenic sounds, including the effects of oil exploration on baleen and sperm whales and the effects of naval sonar on toothed whales.