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Listening to a Changing Ocean: Broadening the Application of Ocean Soundscapes

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Abstract

The collection of sounds in an ocean environment defines the soundscape and offers information that can be used to understand marine life, weather and climate, and human activity. Strategic and collaborative research initiatives over the past decade have brought researchers together to expand collaborative ocean sound monitoring projects to monitor and compare global soundscapes. The insights a soundscape provide depend on what matters to those listening and myriad approaches exist to discover, analyze, and visualize soundscape data. Here, we categorize soundscape insights to highlight the broad use of ocean soundscapes as a practical, inherently holistic, and integrative tool for understanding and responding to dynamic and changing ocean environments. As the ocean sound research community continues to progress in developing and adopting standards and open-source data products, insights from ocean soundscape are becoming more accessible for broader ocean science applications. Mobilizing soundscapes as a tool for serving broader societal needs requires broader engagement to define what information matters and how the knowledge is applied. Here, we explore potential partnerships where ocean soundscapes may provide useful insights. Sustained monitoring efforts, data storage, processing, and visualization infrastructure, and collaborative opportunities are necessary to support these broader engagement efforts. By listening to the ocean with purpose and partnership, ocean soundscapes can become a cornerstone of evidence-based action in a rapidly changing world.

Discovering Ocean Soundscapes

Ocean soundscapes provide a way to understand a place through sound, capturing the acoustic environment as experienced by an individual listener— whether an instrument anchored to the seafloor or an animal moving through an ecosystem. The soundscape encompasses the collection of sounds at any given time, rather than simply individual sources (Erbe et al., 2016;

Pijanowski et al., 2011; Schoeman et al., 2022). The International Organization for Standardization defines ocean soundscapes as the "*characterization of the ambient sound in terms of its spatial, temporal and frequency attributes, and the types of sources contributing to the sound field*" (ISO/TC 43/SC 1, 2014). Soundscapes are complex, often comprised of overlapping sounds from a variety of sources, including animals, human activities, and the physical environment, such as wind and waves at the surface or the movement and calving of ice in polar oceans. The physical environment around where sounds are received (e.g., bathymetry, substrate) also influences how sound propagates and is therefore received at a particular location. The geography and season determine which biological and anthropogenic sound sources are most likely to occur, shaping the composition of a local soundscape. What a soundscape ultimately reveals depends on interests and capabilities of the listener and the tools available to perceive and interpret it.

Advances in sound monitoring technologies and analytical tools have dramatically expanded our capacity to use passive acoustic data to characterize the attributes and sources of soundscapes, allowing us to observe dimensions of the marine environment that are otherwise inaccessible to human observation. Methods range from quantifying sound energy in defined frequency bands for a targeted source or event detection to decomposition of broadband sound energy to identify all sources present (McKenna et al., 2021a; van Geel et al., 2022). These methods reveal the full diversity of biological, geophysical, and anthropogenic sounds that characterize a soundscape, transforming ocean sound data into opportunities for discovery and enabling us to explore what exists within an ecosystem before we know what may ultimately prove most important for science, conservation, or resource management. Discovery, in this sense, is not the end goal but the first step toward understanding what can be revealed through sound.

Discovery efforts characterize the soundscape by establishing baseline conditions, identifying the presence and composition of biological, geophysical, and anthropogenic sound sources, describing their spatial distribution, and quantifying their relative contributions to the overall soundscape (Table 1). Discovery may involve detecting the presence and patterns of key biological sound sources (Oestreich et al., 2020), documenting the absence or reduction of expected sounds, such as wind-driven noise (Hildebrand et al., 2021), or combining detections from multiple sound sources to characterize patterns of overlap, seasonal dynamics, and ecosystem composition (Van Opzeeland and Boebel, 2018). Discovery extends beyond identifying individual sound sources to understanding distribution of sources in time and

frequency space, as well as their relative acoustic contribution to a soundscape. Sound fields, developed by combining known source locations with sound propagation models, reveal where sounds are likely to be experienced, while sound budgets quantify the contribution of different source types to the overall acoustic environment (Tyack et al., 2023). Together, these complementary soundscape observations establish a comprehensive baseline, providing the foundation upon which ecological, environmental, and management insights can be developed and provide context for interpreting change.

Realizing the potential of soundscapes as an integrative tool for understanding and responding to ocean change requires making discovery accessible. Whether through visualizations, interactive data portals, open-access datasets, storytelling, or scientific publications, communicating what ocean soundscapes reveal allows those other than ocean sound specialist to understand and appreciate what is possible (for example, see Sanctuary Soundscape Monitoring Project, 2022). By expanding the potential audiences who can perceive and engage with these discoveries, the ocean sound community lays the foundation for the next stage: transforming discovery into scientific application and societal insight.

Understanding Ocean Systems Through Sound

Discovery methods for ocean soundscapes generate a wide range of information which can be categorized in many ways— by ecosystem type, physical conditions, management or societal context. Here, we focus our categorization on the types of insights that ocean soundscapes can provide about the functioning of the ocean as a system: ecosystem and habitat condition, recovery and resilience, sensory experience, and outcomes of human activities and conservation actions. This framework emphasizes the value of soundscapes as an inherently holistic observing approach that simultaneously captures biological communities, environmental conditions, and human activities. Viewed collectively, these insight categories illustrate how ocean soundscape data can provide an integrative and practical means of understanding and responding to change across marine systems.

Rather than provide a comprehensive review of existing studies within these categories, Table 1 presents a concise set of illustrative examples designed to be accessible to readers across disciplines. We present examples of both **soundscape discoveries**— ways to characterize the soundscape to understand the sources and conditions— and **soundscape insights**. For each soundscape insight category, examples applications are provided with brief descriptions of methodology and approaches.

Collectively, these examples illustrate the remarkable versatility of ocean soundscapes as a tool for understanding marine ecosystems and monitoring ocean change. Table 1 offers entry points for initiating ocean soundscape research towards specific insights about ocean systems. The examples also aim to highlight the diversity of analytical methods that have emerged to address specific scientific questions. As the field grows, however, there is increasing need for standardized soundscape products that serve as a foundation for research needs across disciplines, regions, and observing programs. Standard products are not intended to replace specialized analyses; rather, they provide a common language that enables discoveries to be compared, synthesized, and scaled. Following a community consensus allows researchers to continue developing novel methods while ensuring that core soundscape observations can support coordinated ocean monitoring and global assessments. It becomes the foundation— not a replacement for innovation.

Table 1: Soundscape Discovery – Characteristics and Conditions

Soundscape Discovery	Soundscape Observation	Soundscape Product	Example Finding
Baseline conditions	acoustic detections	duration of time periods with no identified vessel noise presence	Shorter noise free intervals during daytime hours, Figure 6 (Haver et al., 2023)
	acoustic detection	recombine data from multiple biological acoustic detections to understand temporal patterns	Biological contributors to the soundscape shifted seasonally, Figure 3 (Baggett et al., 2026)
	power spectral densities	overall consistency of sound levels over time	Lowest variation in low-frequency sound levels found at American Samoa site when compared across US regions, Figure 5 (Haver et al., 2025)
Presence and/or composition of sound sources	sound pressure levels	quantify deviation from expected conditions	4 dB above expected wind noise at 100 Hz (Hildebrand et al., 2021)
		measure sound levels above threshold in frequencies dominated by known sound source	Seasonal fin and blue whale presence from whale call index, Figure 6 (Pearson et al., 2023)
	acoustic detections	recombine data from acoustic detections and/or non-acoustic data sources	Seasonal multi-species presence, Figure 2 (Van Parijs et al., 2023)

	long-term spectral averages (spectrograms)	manually logged fish chorus events based on energy patterns in spectrograms	Fish chorusing was clustered in time during prime chorusing season, Figure 4 (Kim et al., 2025)
Spatial distribution of sound	sound propagation models and known source presence	map of the sound field from known sources	see SATURN project vessel noise sound maps for marine spatial planning (https://www.saturnh2020.eu/)
Energy contribution of sound sources	acoustic detections and sound levels	use acoustic detections and non-acoustic data sources to model statistically relationships to sound levels	Biological sources dominated the soundscape in summer months at Arctic site. Figure 5 (McKenna et al., 2021b)
	sound propagation models and known sources	use know the acoustic energy emitted by all sources in an area	Container ships account for 57% of sound budget, Table 2.1 (Tyack et al., 2023)

Soundscape Observation *- defined as the feature of the ocean sound environment used to characterize a soundscape (e.g. sound level metrics in a defined time frequency resolution from passive acoustic monitoring or sound propagation model results)*
Soundscape Product *- defined as how observations are summarized to characterize the component of interest in the soundscape.*

Soundscape Insights – Applications and Approaches

Soundscape Insight	Description	Example Application	Soundscape Approach
Ecosystem and Habitat Condition	bioacoustic surveys can help detect certain cryptic, soniferous species for use in tandem with other biodiversity surveys	Bioacoustic measurements complement visual biodiversity surveys: preliminary evidence from four shallow marine habitats	**Low band acoustic measurements** were positively correlated with cryptic fish richness and abundance (Staaterman et al., 2017) Because sounds are ubiquitous in coral reef ecosystems, monitoring soundscapes has the advantage of providing a rapid assessment of a coral reef ecosystem (Lin et al., 2023)
	a holistic measure of ecosystem	Differentiate protected from unprotected areas to ensure the fishing community's food security and economic livelihood is protected	**Direct listening and average spectrogram analyses** detects

	and habitat condition, capturing the biological, physical, and anthropogenic characteristics that define a place and how they vary across space and time		qualitative differences and individual sound sequence; **Soundscape labeling** computes quantitative indices that aligned with the established knowledge of fish assemblages (Brochier et al., 2025)
		Rapid multidimensional and direct comparisons of salient soundscape properties across space and time to define the uniqueness of a location or habitat	**Soundscape Code** uses a collection of soundscape metrics, statistical measures, and acoustic indices selected to quantify properties soundscapes and statistically evaluated for best combination to describe unique soundscape (Wilford et al., 2021)
Recovery and Resilience	because soundscapes capture signals from different components of ecological communities and their environments, they can provide a means of tracking ecological recovery and evaluating the resilience of marine ecosystems following disturbance or restoration	Healthy and restored soundscapes exhibited a similar diversity of biotic sounds; acoustic monitoring can provide complementary information to evaluate restoration success	**Phonic Richness** identifies biophonic sources in acoustic recordings using distinct sound types for unknown sources (Lamont et al., 2022) **Acoustic Community** identifies a component of the ecological that is present during a specific restoration phase (La Manna et al., 2024)
	acoustic signals of reef organisms indicate behavior and can provide a way to evaluate	Mid-stage restored reefs and on healthy reefs exhibited increased ecosystems functioning compared to degraded reefs	**Increase Over Degraded Habitat** - provides a measure of change in ecosystems processes based on the cuescape (Williams et al., 2025)

	ecosystems processes		
Sensory Experience and Acoustic Habitat	offer an effective framework for assessing the ecological outcomes of human activities and the performance of conservation and management actions, enabling evidence-based evaluation across diverse marine settings	Routine vessel passages reduced communication space by up to 62% for fish and 87% for whales; this influence of vessel noise on communication space exceeded natural variability	**Communication Space** is the area over which animals are able to communicate under varying background noise conditions with or without human sources present (Putland et al., 2017) **Communication Masking** is the reduction in area over which animals are able to communicate during human activity. Fin, humpback and minke whale signals experience masking levels of 80% or more with presence of vessel activity in protected area (Cholewiak et al., 2018)
	reveal the acoustic environments experienced by marine organisms, offering insights into how natural and human-generated sounds influence communication, behavior, habitat use, and in some cases survival	Median noise exceedance was >10 dB (90% decrease in listening area) in 20% of all Protected Area units in contiguous US	**Noise Exceedance** is the amount that anthropogenic noise raises sound above natural levels. Threshold noise exceedance values of 3 and 10 dB were used to summarize noise pollution, indicating a doubling and 10-fold increase in acoustic energy due to anthropogenic noise and a 50 and 90% decline in listening area (Buxton et al., 2017)
Evaluation of Human Activities & Conservation Actions	slower ships produce less underwater noise (in most situations); therefore, reducing ship speeds reduces the	**Blue Whale Blue Skies**, vessel speed reduction (VSR) program https://bluewhalesblueskies.org/impact/reducing-underwater-noise/	The 2025 VSR program reduced acoustic intensity from participating ships by 70%; underwater radiated noise of participating ships was reduced by 5.2 decibels compared to baseline, corresponding to a 45%

	contribution of ship noise in marine habitats		reduction in sound pressure levels
		Enhancing Cetacean and Habitat Observation (ECHO) Program https://www.portvancouver.com/environment/healthy-ecosystem/echo	Cumulative participation rate in 2025 was 85% – which translates to more than 5,300 slower or more distanced ship transits within key areas of southern resident killer whale critical habitat
	detecting marine mammal signals can alert mariners to presence of vulnerable species and avoid negative interactions	**Robots for Whales** https://robots4whales.whoi.edu/	Multiple acoustic platforms (mobile and stationary) are detecting and transmitting species presences in endangered right whale habitat

Scaling Ocean Soundscapes for Science and Society

The breadth of soundscape insights demonstrates the tremendous potential of ocean sound monitoring. Realizing this potential at regional to global scales, however, requires moving beyond individual studies toward coordinated observing systems capable of producing consistent, comparable observations across locations and through time. Scaling ocean soundscapes is not simply a matter of collecting more data— it requires common products, thoughtful observing strategies, and sustained partnerships that allow soundscape information to contribute alongside other ocean observations (Tyack et al., 2023).

The Global Ocean Observing System (GOOS) recently identified ocean sound as an Essential Ocean Variable (EOV), one of the few interdisciplinary EOVs, with data available at scales necessary for integrated monitoring (Martín Míguez et al., 2026; Tyack et al., 2023; Tyack, 2017). This recognition of ocean sound as a fundamental component of ocean observation elevates its role from a specialized research tool to a core element of sustained global monitoring. Further, the EOV framework promotes standardized observations, interoperable data products, and coordinated monitoring across regions, enabling ocean sound to be integrated with other ocean observations to support broader science and societal needs. The implementation plan for the ocean sound EOV identifies the use of ocean sound to understand

ocean change, health, and impact by observing sources, trends, soundscapes, and sound fields (Tyack et al., 2023). Combining discovery and insight applications, the ocean sound EOV implementation plan defines a strong and essential foundation for scaling ocean sound monitoring and ultimately expanding the use of ocean soundscapes to serve these needs.

The ocean sound community is already moving towards standardized soundscape data products, open-source data portals, and addressing big data challenges by building cyberinfrastructure for cloud-processing, sharing data, and developing tools (Wall et al., 2025). Historic and ongoing ocean sound monitoring programs that operate at regional to global scales with nested designs across habitats and ocean-use types are contributing to this collective effort in various capacities. For example, recognizing the importance of interoperable soundscape products, an international group of scientists developed the hybrid-millidecade metric as a standardized representation of ocean soundscapes (Martin et al., 2021). The hybrid-millidecade metric was designed to maximize frequency resolution at lower frequencies, retain minute-level temporal resolution, and reduce data volume by grouping higher frequencies (>435 Hz) into millidecade bands. While the hybrid-millidecade metric represents one standardized approach for characterizing ocean soundscapes, it is not intended to replace the diversity of analytical methods that continue to drive scientific discovery nor other standard approaches built for other large-scale projects (Basan et al., 2024). Rather, it provides a common, scalable product that supports comparison across studies and observing programs while serving as a foundation upon which more specialized analyses can be developed. As adoption of the hybrid-millidecade soundscape metric has grown, together with open-access data repositories and community-developed interpretation tools (Sakai et al., 2025), researchers are increasingly able to explore and use standardized soundscape products to answer a variety of research questions and develop support tools to serve various management needs.

Standardized soundscape products ensure that observations are generated consistently, but meaningful comparisons depend on thoughtful observing system design. In other words, standard products only become useful when placed and applied within environmental and societal context. With the implementation of ocean sound as an interdisciplinary GOOS EOV, current networks with additional strategic, coordinated, and integrated observing efforts are necessary to sustain a global network of sensors to deliver ocean sound observations relevant for climate change, ocean health, and monitoring threats. Site selection, habitat representativeness, deployment consistency, and environmental context are equally critical for distinguishing true ecological change from differences introduced by where and how

measurements are collected. These considerations become increasingly important when tracking long-term trends in complex socio-ecological systems, where natural variability, climate change, and human activities interact across multiple spatial and temporal scales (ZoBell et al., 2025). Specifically, observing efforts to address global decision spaces require strategic placement of monitoring locations to capture the intended dynamics for tracking status and trends (e.g. vessel underwater noise reduction efforts through the International Maritime Organization and environmental impact assessments from maritime activities in the High Seas Treaty Biodiversity Beyond National Jurisdiction, as well as species monitoring for establishing high seas marine protected areas). In some cases, soundscape monitoring locations will serve multiple purposes, and others will be dedicated to monitoring specific trends (e.g. ocean noise from vessels; Hatch et al., 2025). Carefully designed observing networks provide the high-resolution, long-term records needed to separate transient events from sustained change, identify emerging trends, and attribute changes to underlying ecological and/or anthropogenic drivers. By combining standardized products with strategically designed monitoring programs, ocean soundscapes can provide a robust foundation for detecting, understanding, and responding to change in a rapidly changing and increasingly managed ocean.

Coordinated observing networks, standardized products, and thoughtful monitoring design provide the technical foundation needed to scale ocean soundscapes for science and society. And, for over a decade, strategic research initiatives have advanced ocean sound monitoring into an integral component of the global ocean science community, yet this technical capacity alone is insufficient. The ultimate value of ocean soundscape observations and insights depends on their ability to answer questions that matter to the people responsible for managing and using the ocean. Understanding the social context in which soundscape information can inform decisions— from local stewardship to international policy— requires engagement with the communities who will use these observations and insights (Bennett et al., 2025; Crosman et al., 2022; Österblom et al., 2023). Importantly, ocean observing is at a critical stage of maintaining connections to society to sustaining these vital monitoring systems (Lehman et al., 2026).

Building Collaborations beyond the Ocean Soundscape Community

As ocean sound monitoring continues to mature and expand, more partnerships are emerging to ensure that ocean soundscapes are relevant, accessible, and actionable. How does the ocean soundscape community sustain these partnerships?

First, standardized and openly accessible soundscape observations create opportunities for many new users, especially when these are paired with visualizations, interactive data portals, and storytelling allowing others to discover and appreciate what is possible. Further, integration with other ocean observations and familiar platforms increase exposure and accelerate incorporation into existing frameworks as a complementary observation that when interpreted together produce insights at relevant scales and contexts.

Building societal relevance then requires moving beyond sharing information towards co-production of knowledge from ocean soundscapes, where observing priorities, interpretation, and products are developed collaboratively with intended the users. One approach is co-designing technology, monitoring locations, and soundscapes products around decision needs. For example, various communities are often interested in understanding if biodiversity targets are being met. As Table 1 highlights, soundscapes can reveal habitat condition and recovery which both provide useful insights in this decision space. Potential partners therefore might include maritime businesses interested in tracking sustainability targets or countries tracking climate objectives for restoring or protecting ocean habitats to meet nationally determined contributions. Partnerships grounded in co-management can help ensure that soundscape insights are shaped by local priorities, integrated with other knowledge systems, and translated into decisions that support shared sustainability and stewardship goals.

The most transformative applications of ocean soundscapes may not yet be known. As ocean sound observations become more accessible and are interpreted by increasingly diverse communities, new questions, partnerships, and applications will emerge that extend well beyond those envisioned by the ocean sound community alone. The most relevant soundscape insights will likely emerge from the priorities and capacities of partner communities, rather than from predetermined scientific questions or products. Realizing the societal value of ocean soundscapes will depend on investments in the social infrastructure needed for collaboration.

Listening with purpose and partnership

What began as a valuable tool for characterizing ocean sound environments is now poised to inform ocean solutions: supporting adaptive management, guiding sustainable maritime practices, and tracking progress toward climate and conservation goals. Further, finding accessible and relatable ways to connect people to the ocean through sound, using community science and outreach via public media[1], can be a means to restore a widening gap between science and humanity. By listening to the ocean with purpose and partnership, ocean soundscapes move beyond observation to become a cornerstone of evidence-based action in a rapidly changing world.

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