International Science Council
SCOR
Scientific Committee on Oceanic Research

IQOE
International Quiet Ocean Experiment

pogo
Partnership for Observation of the Global Ocean

# OCEAN SOUND
## Essential Ocean Variable
# Implementation Plan

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# CONTENTS

# EXECUTIVE SUMMARY

This document provides guidance for the addition of acoustic observations to the Global Ocean Observing System (GOOS) through implementation of the Ocean Sound Essential Ocean Variable (EOV). The goal of this *Ocean Sound EOV Implementation Plan* is to define a baseline of how ocean sound observations are collected, analyzed, managed and reported.

## 1 Why is sound an important variable for observing the ocean at a global scale?

Of all the ways to transmit energy or information through the ocean, sound reaches the farthest. Acoustic sensors are the only ones for which a network of only a dozen stations can detect high-intensity, low-frequency signals produced by events almost anywhere in the global ocean. Modern digital electronics make it possible to produce small cost-effective ocean acoustic recording systems, which enable persistent observations from a variety of platforms in all seasons and all ocean areas.

Ocean sound is a physical variable: variation in pressure or particle motion that propagates through seawater. But sound is also a cross-disciplinary EOV, because these physical vibrations can carry information about many objects and processes in the ocean. GOOS has defined three core delivery areas into which observations can help society: (1) understand and manage changes to climate, (2) maintain ocean health, and (3) operational services that monitor threats and provide forecasts and warnings. Observations collected as part of the Ocean Sound EOV meet different requirements of all three core delivery areas, as the following examples indicate:

- Climate Change: extent and breakup of sea ice, frequency and intensity of wind, waves and rain
- Ocean Health:
  - Biodiversity assessments: monitoring the distribution and abundance of sound-producing species
  - Environmental impacts: forecasting, monitoring, and mitigating impacts of human activities on wildlife
- Monitoring Threats: nuclear explosions, foreign/illegal/threatening vessels, monitoring human activities in protected areas, and underwater earthquakes that can generate tsunamis

Most marine organisms detect the particle motion component of sound, which can be difficult to predict based upon pressure measurements for locations near the seafloor or surface. This suggests the need for more measurements of particle motion in locations where the effects of sound on relevant marine life is a priority.

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## 2 Who manages the Ocean Sound EOV?

The Ocean Sound EOV provides a framework for passive acoustic observations that will advance our use of sound to understand the ocean. The Ocean Sound EOV will require coordination and standardization of observations that will advance our ability to document and understand changes in ocean sound over space and time, to understand how different sources of natural and anthropogenic sound affect ambient ocean soundscapes, the effects of sound on marine life, and how acoustic monitoring can be used to assess biodiversity and ecosystem health.

GOOS provides a global framework for international collaboration, but it does not manage or fund any observation systems itself, nor does it provide long-term archiving for ocean observations and the data that underlie them. Implementing the Ocean Sound EOV will therefore require support from interested national and regional governments and dedicated support from expert teams in ocean acoustics, measurement systems, analysis relevant to each application, and data management.

## 3 What is the path from acoustic recordings to societally important ocean observations?

**3a. Trends in underwater sound:** There are many uses for data on trends in underwater sound. Navies listening for ships need to know the ambient sound fields. Ocean noise is a stressor for wildlife, so it is important to know whether and where the stressor is increasing or decreasing. Well-calibrated recordings from the same site can provide important data on changes in ocean sound over time, but there are few published data on the trends of ocean sound, and no global or regional analogs to the Keeling Curve for atmospheric carbon dioxide.

**3b. Mapping ambient sound fields:** The sound field is usually defined as the distribution of sound pressure as a function of location (x, y, z) and time (t). This adds a spatial component to sound observations from specific sites. Mapping of sound fields requires modelling of sound propagation in the ocean using propagation parameters as supporting variables.

**3c. Soundscapes:** Soundscapes characterize what sound sources create a sound field. The ability to develop models that accurately predict changes in soundscapes as a function of human activities or natural factors would be extremely valuable to users and managers of ocean sound. Acoustic recordings of identified sound sources allow us to characterize sound source signatures. This information about the acoustic characteristics of sound sources and about their distribution in time and space is essential for understanding soundscapes. Given information about the acoustic characteristics of each sound source and the location and transmission times of each source, propagation modelling can be used to predict how the three-dimensional sound field generated by the sources changes over time. These models can be used to predict changes in sound fields expected for proposed deployments of well-characterized sound sources, which is needed to assess the environmental impact of sound-producing activities. Measurements of ocean sound at appropriate recording sites can be compared to output of sound propagation models throughout wider ocean areas to validate the predictions of these models.

**3d. Detecting transient signals from specific sound sources:** Information about the precise signals produced by different sound sources can be used to detect and classify transient sounds according to the sources that produced them. These data can be used to monitor the distribution of abiotic sources such as wind, waves and ice (part of the GOOS "Climate Change" goal), of biotic sources such as soniferous species (part of the GOOS "Ocean Health" goal), and of natural abiotic sound sources such as earthquakes or tsunamis that are threats to humans and vessels, and human-made sound sources such as airguns and sonar that are threats to wildlife (part of the GOOS "Monitoring Threats" goal). The Ocean Sound EOV can facilitate the integration of data from a growing network of ocean sound observing systems into threat warning systems, especially in areas with limited funding where multi-purpose observing systems may be more cost-effective than separate sensor networks for each application.

# 4 How different ways of collecting ocean acoustic data address the Ocean Sound EOV missions

Acoustic sensors can be moored on fixed platforms or deployed on a variety of mobile platforms, including floating or subsurface buoys, autonomous underwater vehicles, towed from ships, or attached to animals. Ocean acoustic data systems can be autonomous recorders or provide real-time connections through cables to shore or using radio and satellite links. Figure ES-1C shows the typical scales of space and time for which these different platforms are typically used, with Figure ES-1B showing the scales of different issues for which ocean observations are made.

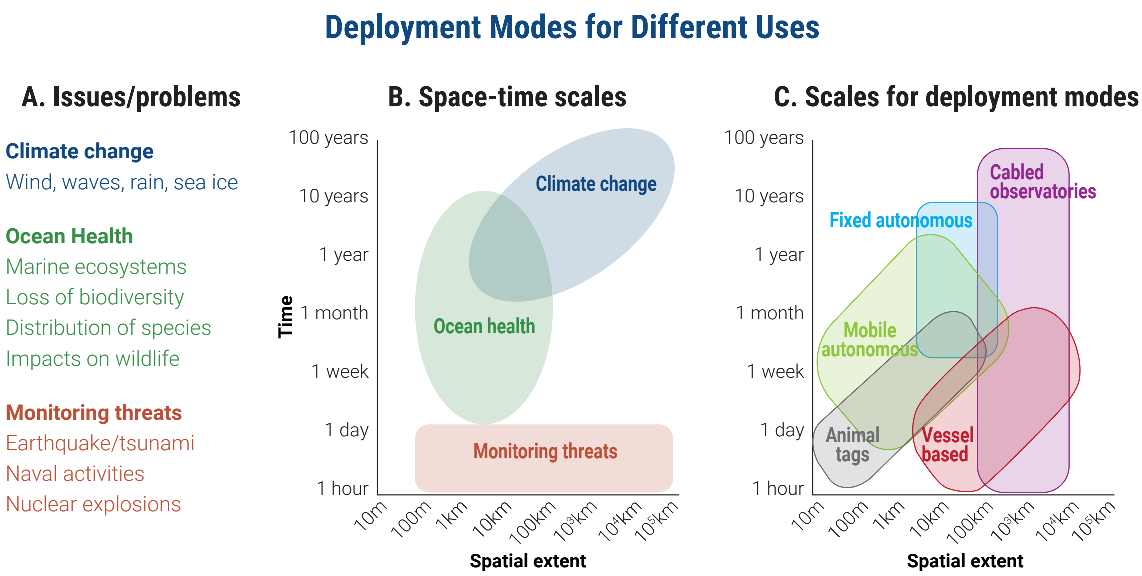


Figure ES-1. Overview of deployment modes for Ocean Sound EOV uses. Figure ES-1A color codes the main societal issues and problems for which the Ocean Sound EOV would provide observations. Figure ES-1B uses the same color code to sketch the space-time scales required for observations relevant to each problem, and Figure ES-1C illustrates the coverage that several modes of deployment of ocean acoustic sensors can provide in terms of space on the x-axis and time on the y-axis.

GOOS and its Observations Coordination Group (OCG) have defined a set of attributes for networks for observation of EOVs in the global ocean (GOOS Report 266). Observations must be designed to be sustained over many years, beyond the lifespan of individual research projects or experiments. They should be designed for spatial scales that are larger than regional, with an intention for global coverage. GOOS uses a variety of criteria to evaluate the readiness level of observing systems. The ocean acoustic measurement system of the Comprehensive Test Ban Treaty Organisation (CTBTO) is one of the most mature systems, having operated for decades a network of hydrophone stations that cover the global ocean. The ALOHA Cabled Observatory does not have a global scope but can provide open access to data in near real time. Hundreds of ocean bottom seismometers (OBSs) are deployed at any time in the global ocean to measure geophysical activity, but OBSs also measure low-frequency ocean sound. Coordinating sensors and recordings for multiple purposes on OBS platforms may reduce costs associated with the collection of observations and add to global assets able to monitor ambient ocean sound, including sounds produced by wildlife. An example of a mature array of mobile platforms contributing to GOOS is the fleet of >4,000 Argo floats which can sample ocean data from the surface to 2,000 m depth. These floats would be excellent platforms for acoustic recordings, and the Ocean Sound EOV can help to advocate for including acoustic sensors on these and other developing observing platforms.

A major contributor to the Ocean Sound EOV will be a global hydrophone network that will require management and data functions different from most other EOVs. This network could apply to be a GOOS Emerging Network, which includes networks that have shown progress toward becoming an OCG network, but still need to demonstrate that they can achieve some of the attributes required of mature networks. The goal of this Ocean Sound EOV Implementation Plan is defining a baseline of how ocean sound is collected, analyzed, managed and reported.

# 5 Developing and managing an open-access digital archive of ocean sound data

To produce global datasets and products, measurements must be collected and/or processed in such a way that they are comparable over space and time, by whatever instruments or observation methods are used. To achieve comparability of acoustic measurements, it is important to identify and reduce variations in measurements that result from differences in sensors, how they are calibrated and used, and how data from these instruments are analyzed and archived. The establishment of systems to serve acoustic data submitted by scientists from their nations requires standardized analysis programs. Data and complete metadata must be provided with open access for real-time and delayed data delivery. GOOS requires that observation systems develop and follow standards and best practices for all these tasks.

An early stage of implementing the Ocean Sound EOV will involve a meeting of generators and users of ocean sound data to discuss what data products need to be linked at the global level through GOOS, with data freely accessible and able to be turned into the derived data products discussed in Section 2. They will need to establish:

- How can the quality of calibrated data be controlled? What criteria are necessary for evaluation of data quality? What organization coordinates or conducts the validation/evaluation process?
- What data are required for users to generate the derived data products?
- How can derived data products be developed that answer societal needs while alleviating intellectual property and national security concerns?
- How rapidly do acoustic data need to be released for each data product? What are the obstacles, if any, to rapid enough release?
- How can ocean sound data be efficiently and reliably processed into the required derived data products and observations?
- What institutional settings are best situated for long-term curation, archiving and distribution of these data and the derived data products?

Establishing clear responses and actions to these questions is a critical goal of this implementation plan. This will then need to be followed up with assessments of whether archives are developing in a way that meets the requirements of the Ocean Sound EOV specification sheet.

# 6 How can the Ocean Sound EOV be governed and funded?

## 6.1 Governance of existing GOOS networks

Implementation of the Ocean Sound EOV will require at least four activities: (1) establishment of a coordination function for an international hydrophone network, (2) establishment of a Quality Assessment and Quality Control (QA/QC) function for acoustic data, (3) coordinating and ensuring long-term availability of acoustic data records, and (4) capacity building and increasing availability of calibrated and cost-effective systems for recording underwater sound. We anticipate that the initial stages of implementing the Ocean Sound EOV will come from user groups of experts in each of these four different areas. Each of these activities may be able to grow from ongoing working groups of the International Quiet Ocean Experiment (IQOE).

## 6.2 Funding for ocean acoustic observations

Funding for observing systems is comprised of funding for instruments, deployments, analysis, data management, and international coordination. These functions are mainly funded by individual nations. International coordination of observing activities and, in particular, the collection of physical and biogeochemical observations (e.g., Argo) is often supported by one or a few nations, often in combination with national coordination of the activities of each host nation. Here, we envision that management of national ocean sound data would be similarly supported by the participating nations, while international coordination of observing assets and providing data access is supported by one or more participating nations.

One of the aims of formalizing an Ocean Sound EOV is that it provides a recognized mechanism through which national agencies can make the case to provide sustained funding for ocean acoustic observations, as has occurred with other observing assets that contribute to other GOOS EOVs, such as Argo floats, tide gauges, and data buoys. The termination of funding for some national acoustic observation networks highlights the need for national commitments to maintain long-term observations appropriate for GOOS. Products with demonstrated utility for research, management, and public outreach are critical for justification of continuous funding.

## 6.3 GOOS models for supporting ocean acoustic observations

GOOS coordinates a set of observation networks through the GOOS Steering Committee and the GOOS Observations Coordinating Group (OCG). Most of these networks are organized by platform rather than by sensor, but the ocean sound network will likely be organized by acoustic sensors. Most OCG networks have long been managed by intergovernmental bodies, such as the Intergovernmental Oceanographic Commission (IOC) of UNESCO and the World Meteorological Organization (WMO). Tracking of the assets of these different networks and international data access is maintained by the Observations Programme Support Centre (OceanOPS). Each network has a Technical Coordinator or Technical Secretary based at OceanOPS or IOC. These individuals serve as the coordinator for OceanOPS activities related to their system. Observation networks may also incorporate executive committees or other advisory groups that oversee the technical work of the systems and usually comprise members from countries that deploy observing assets for the system. As the ocean sound observing networks mature, ocean sound should become integrated into one coordinated ocean sound observing system.

### 6.4 Public awareness efforts that can help build support for existing and new systems

Implementing the Ocean Sound EOV will require outreach and involvement of communities that will use or be informed by the data products resulting from the observations. As described above, the derived data products are important for a broad array of user groups. Data on sound in the ocean is important for marine industries whose production of sound is regulated, and for organizations concerned about ocean sound as a stressor for marine organisms. Public interest in observations collected as part of the Ocean Sound EOV will also be important for maintaining political pressure to continue governmental funding during challenging budgetary environments.

## 7 Proposed tasks to implement ocean acoustic observations for GOOS

The following list of tasks is described in detail in the last chapter of the implementation plan:

7.1 Set up international coordination for observations from hydrophones and particle motion detectors

7.2 Maintain the existing global set of hydrophones and particle motion detectors and historic ocean sound datasets

7.3 Foster inclusion of particle motion sensors and their deployment systems where needed

7.4 Review existing deployments of ocean acoustic sensors, identify gaps in coverage and propose how to mature them into a GOOS observation network

7.5 Develop standards for GOOS-compatible underwater acoustic recording systems and explore adding acoustic sensors to existing GOOS networks

7.6 Establish working group(s) on calibration, standardizing data analysis, and data management

7.7 Develop standardized open-access databases of ocean sound produced by known human, biotic, and abiotic sources

7.8 Develop low-cost underwater acoustic measurement and recording systems for educational and citizen science applications

7.9 Engage with industry and regulators along with ocean acoustic modelers to develop hindcast, nowcast and forecast ocean soundscape scenarios

7.10 Reach out to policymakers, industry representatives, the media, and other stakeholders

7.11 Develop a self-sustaining observation network for the Ocean Sound EOV

# 1 INTRODUCTION

This document provides guidance for the addition of passive acoustic observations to the Global Ocean Observing System (GOOS) through implementation of the Ocean Sound Essential Ocean Variable (EOV). GOOS is a program led by the Intergovernmental Oceanographic Commission (IOC) of UNESCO to coordinate institutional, national, regional, and international observing systems. GOOS was developed under the auspices of IOC, the International Science Council, and the World Climate Research Programme in response to calls from the Second World Climate Conference in 1990. Expert panels of GOOS select EOVs that can be measured worldwide via observing systems contributing to GOOS and that are critical for understanding the status and trends of the ocean environment. Multiple EOVs have been identified across the GOOS Physics, Biogeochemistry, and Biology and Ecosystem panels. Many EOVs measure ocean parameters by deliberately adding sound to the environment. In contrast, the Ocean Sound EOV extracts information about the ocean by interpreting the information available just by listening to the ocean. The Ocean Sound EOV is a cross-disciplinary EOV with a lead responsibility from the Biology and Ecosystems Panel. The International Quiet Ocean Experiment (IQOE: www.iqoe.org) led the development of the Ocean Sound EOV specification sheet and implementation plan for the EOV under the auspices of the Partnership for Observation of the Global Ocean and the Scientific Committee on Oceanic Research.

This is a non-technical document that is designed primarily to guide contributors, users and managers of ocean acoustic observing systems and national funding agencies to take the next step in implementing the Ocean Sound EOV through which ocean acoustic observations can contribute to GOOS and via GOOS into regional and global assessments of the marine environment.

## 1.1 Why is sound an important part of the Global Ocean Observing System?

Our human intuition about how far different senses can detect objects is biased by the terrestrial world in which we live. We are accustomed to light being the best way to sense distant objects in air or in space. But as any diver knows, light does not penetrate far in seawater. By contrast, sound travels so efficiently in seawater that it is the best way to sense distant events and processes in the ocean. Some loud low-frequency sound sources—such as earthquakes, baleen whales, nuclear explosions and seismic surveys—can be heard more than 1,000 km away in the ocean. This means that fewer than a dozen carefully located listening stations can form a global observation system that can detect loud low-frequency underwater sound sources almost anywhere in the global ocean (Howe et al. 2019a). Even higher frequency sounds, which propagate less efficiently and tend to be less loud, can be heard for significant distances underwater. No other ocean variable can be sensed over such long ranges or can cover the ocean with so few fixed monitoring stations.

Ocean sound is a physical variable: the time series of pressure or particle motion that propagates through seawater. But sound is also a cross-disciplinary EOV, because these physical vibrations can carry information about many objects and processes in the ocean. Observations of ocean sound are useful for anyone interested in any of the following topics:

- Climate change: extent and breakup of sea ice, frequency and intensity of wind, waves and rain from extreme weather events, such as cyclones
- Threat monitoring: nuclear explosions, foreign/illegal/threatening vessels, and underwater earthquakes that can generate tsunamis
- Biodiversity assessments: monitoring the distribution and abundance of sound-producing species
- Environmental impacts: forecasting, monitoring, and mitigating impacts of human activities on wildlife

Some of the most immediate impacts of **climate change** for coastal communities and offshore activities of humans are associated with increased frequency and intensity of storms. Storm-driven wind and waves can pose a direct risk to humans. Rain at sea poses less of a risk, but measures of rainfall yield important data for climate models. Changes in sea ice, some of which are caused by climate change, generate sound, modify noise caused by wind-driven waves and affect sound propagation. Acoustic measurements can monitor wind, waves, sea ice and rain over large areas, yielding estimates that are more integrated than point measurements from other instruments. Over time, acoustic sensors can provide important trend information for tracking the impacts of changing weather metrics associated with climate change on the marine environment.

The long ranges over which sound propagates in the ocean have led to the development of systems for **monitoring underwater threats** that rely on acoustic monitoring. During the 1950s, national navies developed arrays of hydrophones to detect the propulsion sounds of foreign submarines at great distances (Howard 2011). The Comprehensive Test Ban Treaty Organization (CTBTO) began deploying a network of underwater acoustic monitoring stations in 2000 to detect nuclear explosions in the ocean, and currently includes 11 stations in its hydroacoustic network: 5 T-phase stations that employ on-land seismometers and 6 hydrophone stations with triplets of hydrophones deployed in the Sound Fixing and Ranging (SOFAR) channel. This array also records earthquakes that could generate life-threatening tsunamis and provides these data to tsunami warning centers. Operational use of these datastreams by warning centers relies on rapid real-time provision of detections, and the more rapidly these acoustic detections are made available, the more effective early warnings will be.

Most approaches to **censusing wildlife** are based on sighting individual organisms. Within the marine environment, however, many species cannot reliably be sighted. Species that produce sounds are often easier to detect acoustically than visually. Over the past decade, acoustic census methods have been developed to estimate the distribution and abundance of marine species that produce sound (Marques et al. 2013). Passive acoustic monitoring (defined in Box 1-1) methods have some advantages over visual surveys in that they are less labor intensive, they are not compromised by sighting conditions, and they are less affected by bad weather. They can also be conducted continuously year-round, extending the monitoring of mobile species and providing key information on incidence, distribution and relative abundance in space and time; information needed for effective conservation management. This ability for persistent monitoring is a significant advantage compared to occasional visual surveys where sightings may be limited to good conditions during the best seasons for observation. An example of such an application is the real-time passive acoustic monitoring of North Atlantic right whales in high-density shipping areas to reduce the risk of vessel collision (van Parijs et al. 2009). Difficulties with visual observations of marine organisms not only led to passive acoustic monitoring of individual species, but also to **monitoring of biodiversity and the health of marine ecosystems**. Acoustic complexity indices of biodiversity assume that "the acoustic output of a community or a landscape will increase in complexity with the number of singing [or calling] individuals and species" (Sueur et al. 2014:774); this logic led to the development of acoustic complexity indices that correlate with species diversity and complexity of some terrestrial ecosystems. Mooney et al. (2020) summarize efforts to use passive acoustic monitoring to assess the health, complexity, and diversity of marine ecosystems.

Over recent decades, anthropogenic ocean sound has become recognized as a pollutant by the UN Convention on the Law of the Sea (UNCLOS). Negative impacts of ocean sound on environmental quality and health have been recognized by the EU Marine Strategy Framework Directive, the Convention for Biological Diversity, the Convention on the Conservation of Migratory Species of Wild Animals, and have been the focus of the United Nations Informal Consultative Process in support of UNCLOS. Responding to these concerns, the second World Ocean Assessment (UN 2021) for the first time included a chapter on inputs of anthropogenic ocean sound.

Passive acoustic monitoring can contribute to understanding **the effects of human activities on** the behavior and distribution of **wildlife**. Motorized vessels produce noise as a by-product of their propulsion systems, but many other human activities use active acoustic sources (**active acoustics** defined in Box 1-1) in the ocean that make specific sounds to detect features or communicate information. Anthropogenic sounds can be a stressor for marine life, causing acute disturbance reactions that can lead to injury or death (de Quirós et al. 2019) and chronic effects such as increased stress and changes in behaviors (e.g., feeding, resting, and socializing) that can affect survival and reproduction (Slabbekoorn et al. 2010). Passive acoustic monitoring provides a means to measure the distribution and intensity of anthropogenic sound, as well as to monitor the responses of sound-producing organisms. The data produced from these methods can be used to inform risk assessments and conservation management.

## 1.2 Definitions

### Box 1.1 Definitions related to sound used in this report.

In this document, we use the ISO 18405:2017 definitions (see ISO 18405:2017(en), Underwater acoustics — Terminology), which are shown in quotation marks. These are technical definitions – see the text below the box for descriptions designed to make them usable by the full range of readers of this document. More accessible explanations are also available at https://dosits.org/.

**Sound:** "alteration in pressure, stress or material displacement propagated via the action of elastic stresses in an elastic medium and that involves local compression and expansion of the medium, or the superposition of such propagated alterations". This term includes all sources, human and anthropogenic, episodic and continuous.

**Signal**: "specified time-varying electric current, voltage, sound pressure, sound particle displacement, or other field quantity of interest"

**Noise:** "time-varying electric current, voltage, sound pressure, sound particle displacement, or other field quantity except the signal or signals"

**Hydrophone:** "underwater sound transducer that provides an electrical signal in response to fluctuations in pressure, and is designed to respond to the pressure of a sound wave"

**Ambient sound:** "sound that would be present in the absence of a specified activity"

**Passive acoustic monitoring:** listening to and recording sound without adding sound to the environment

**Active acoustics:** adding sound to the ocean as a tool to study some aspect of the water column, seafloor, interfaces, and/or organisms

**Sound field**: distribution of sound pressure as a function of three-dimensional location and time

**Spectral Probability Density:** empirical probability densities of frequency bands computed from the power spectral density of multiple sound samples

**Sound Pressure Level (SPL):** the level in decibels for a time-averaged root mean square (rms) sound pressure $p$ with respect to a reference pressure $p_0$ is defined as $20 \log_{10}(p/p_0)$. The SI unit for pressure is the Pascal (Pa) and the underwater reference pressure is 1 μPa.

**Soundscape:** "characterization of environmental sound in terms of its spatial, temporal and frequency attributes, and the types of sources contributing to the sound field"

**Sound budget:** estimates how much of the sound energy at each frequency for a defined time and space derives from each of the relevant sources of sound

What is sound? Sound is a compressional wave that propagates through elastic media such as gases, fluids, and solids. The definition of **sound** in Box 1.1 is the ISO standard definition, but here we expand with a less-technical description. Imagine a sound source in air or water that moves a large plate back and forth in one dimension. As this plate moves outwards into the medium, it moves particles in the medium outwards in the same direction, leading to a compression of the particles. Because the medium is elastic, the motion of these particles causes motion of neighboring particles, leading to a wave of particle motion that propagates outward at a sound speed determined by the properties of the medium. When the plate of the sound source moves back away from the medium, the particles nearby will move back, causing a rarefaction of the particles. Each particle moves back and forth, but the compressions and rarefactions of the sound wave propagate through the medium. Sound waves can be measured either by sensing changes in pressure caused by the compressions and rarefactions or by measuring the actual movement of the particles. A sound field is the distribution of sound pressure or particle motion as a function of three-dimensional location and time. Measurements can seldom cover the whole space and time of interest, so estimating a sound field requires modeling of how sound propagates through the medium, which can be verified by acoustic measurements.

Electronic instruments called hydrophones measure underwater sound pressure. Sound-induced movement of particles in seawater can be detected by accelerometers or arrays of hydrophones specially designed to estimate particle motion by measuring pressure gradients (Nedelec et al. 2021). A **signal** is defined in Box 1.1 as either the physical pressure or particle motion of interest, or voltages or electrical currents generated by instruments that measure the sound field. Many marine animals are able to sense sound in the form of sound pressure and/or particle motion. Here the signal may be the neural representation of sounds of interest that the animal hears. If a naval ship is listening for the propulsion sounds of another naval ship, then the ship sound is a signal and any sounds produced by waves or animals would be **noise**, defined as any energy generated by sound sources other than the source of interest. Note that there is no absolute definition of what is signal and what is noise. In the case of a whale listening for the calls of another whale, the whale calls are the signal and the ship sound is noise.

The signal-to-noise ratio is often used to estimate the probability of detecting or correctly classifying a signal. Many factors affect detectability. If the sound of interest has a different frequency than the sound constituting the noise, or if the sound of interest comes from a different direction than the sound that constitutes the noise, then the signal may be easier to detect. Noise may vary over time, and the signal is easier to detect when the noise is faint than when it is loud. To fully understand how a receiver detects a signal, we need to know about the broader soundscape, that is, the spatial, temporal and frequency attributes of all the sources contributing to a sound field.

## 1.3 Relationship of Ocean Sound EOV to other EOVs and to ocean acoustics

The GOOS Framework for Ocean Observing argues that a global system of observations needs to avoid duplication of efforts across platforms and networks and needs common standards for data collection and dissemination. These common standards were identified as keys for maximizing the usefulness of observations. To address these needs, the framework focuses observations around EOVs. Expert panels identify EOVs and develop associated specifications for each, including observations of importance under three major topic areas: physics and climate, biogeochemistry, and biology and ecosystems. Table 1.1 lists these EOVs, along with three cross-disciplinary EOVs, including ocean sound. The Ocean Sound EOV links to other EOVs either through the Ocean Sound EOV providing information to help interpret other EOVs (indicated in orange font in Table 1.1) or other EOVs helping to interpret ocean sound (indicated in green font).

Table 1.1 EOVs accepted by the Physics and Climate, Biogeochemistry, or Biology and Ecosystems Panels of GOOS (List of GOOS EOVs). The ocean color, ocean sound and marine debris EOVs are considered cross-disciplinary, contributing to the EOVs of each of the three panels and, in turn, EOVs specific to the panels contribute to the cross-disciplinary EOVs. EOVs that can be informed by the Ocean Sound EOV are indicated in orange. Ocean temperature, hydrostatic pressure and salinity affect how sound propagates in the ocean; EOVs related to these variables that affect the Ocean Sound EOV are indicated by a green type font.

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| **Physics and Climate EOVs:** sea state, ocean surface stress, sea ice, sea surface height, sea surface temperature, subsurface temperature, surface currents, subsurface currents, sea surface salinity, subsurface salinity, ocean surface heat flux |
| **Biogeochemistry EOVs:** oxygen, nutrients, inorganic carbon, transient tracers, particulate matter, nitrous oxide, stable carbon isotopes, dissolved organic carbon |
| **Biology and Ecosystem EOVs:** phytoplankton biomass and diversity; zooplankton biomass and diversity; fish abundance and distribution; marine turtles, birds, mammals' abundance and distribution; hard coral cover and composition; seagrass cover and composition; macroalgal canopy cover and composition; mangrove cover and composition; microbe biomass and diversity; invertebrate abundance and distribution |
| **Cross-Disciplinary EOVs:** ocean color, ocean sound, marine debris |

Among the physics and climate EOVs, waves generated by wind produce distinctive acoustic signatures, so sea state can be estimated from acoustic data. Sea ice produces distinctive sounds when it moves and cracks, it can affect sound propagation by altering interactions with the sea surface, and it affects other sounds; for example, wind generates less wave energy when the surface is covered in ice. The physics and climate EOVs of seasurface and subsurface temperature and salinity are important supporting variables for ocean sound because they affect how sound propagates in the ocean. In regard to the biology and ecosystem EOVs fish, marine mammals, and invertebrates such as snapping shrimp generate significant and distinctive sound signatures in some habitats. Sounds from marine species have been used to estimate the type of habitat and quality of habitat, so may also indirectly support the ecosystem EOVs related to habitats.

Figure 1.1 illustrates the relationship between the Ocean Sound EOV and the broader field of ocean acoustics. Ocean acoustic methods are divided into two major categories: active and passive. Acoustic methods that actively generate and add sound to the ocean as a tool to study it are called **active acoustics**, as indicated on the left side of Figure 1.1. **Passive acoustic monitoring**, indicated on the right side of Figure 1.1, does not involve producing any sound, but involves listening to external sounds that can have natural biotic, abiotic or human origins. Active acoustic methods that use human-made sound sources to study objects or processes in the ocean include sonars and echosounders. These technologies contain a sound source and a sound receiver to listen for echoes from the sea surface, sea ice, or seafloor (depth sounder) or from objects in the water column such as plankton and fish. Subsurface currents can be estimated by measuring the Doppler shift of echoes from targets in the water. Other active acoustic technologies separate the sound source and receivers to measure physical properties of the water column such as subsurface temperature. Proposals for using powerful sound sources to measure subsurface ocean temperature globally were abandoned in part because of concern about the impact of these anthropogenic sounds on marine life. Consideration of these impacts has led to innovative development of methods that use passive acoustic monitoring to understand changes in ocean temperature by measuring changes in travel times of sounds of multiple earthquakes from the same site (Wu et al. 2020).

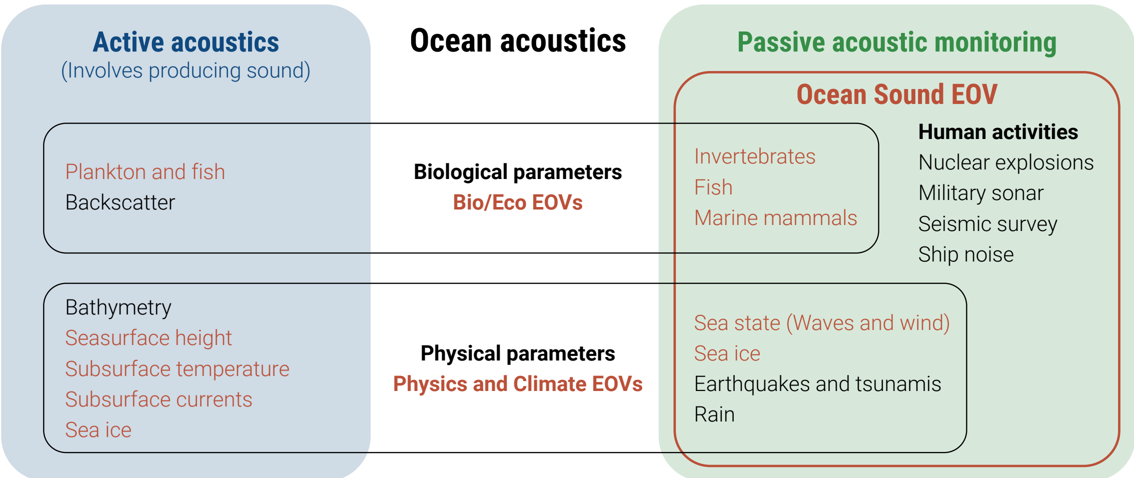


Figure 1.1 Relation of Ocean Sound EOV to other GOOS EOVs (in orange) and other variables (in black).

The Ocean Sound EOV includes passive acoustic monitoring for any sounds in the ocean, whether produced by human sources or natural biotic or abiotic sources. Including active acoustics in the Ocean Sound EOV would deviate from the usage for the rest of the EOVs, which focus on observing the variable rather than introducing the variable into the ocean to study it. For example, the Transient Tracer EOV uses a variety of chemical tracers in the ocean to measure their transport. It does not include experiments that add a tracer intentionally to the ocean to measure ocean properties.

The exclusion of active acoustics from the Ocean Sound EOV is not only important for consistency with other EOVs, but it is also consistent with the most basic GOOS goals. The GOOS 2030 strategy starts with the fundamental goal of maintaining a healthy and safe ocean, recognizing that human pressures on the ocean are mounting. Sound is a stressor for marine life; increasing levels of ocean sound not only pose a risk to marine ecosystems, but they also can harm human activities that seek acoustic signals in ocean noise. The ability of sound to propagate so far underwater makes ocean sound particularly powerful as an EOV that can cover larger spatial scales than other ocean variables. However, intense active acoustic systems pose well documented risks to marine life. The generic inclusion of all active acoustic methods in the Ocean Sound EOV could be viewed as promoting these adverse impacts in contradiction to the GOOS goal of a healthy and safe ocean. Each of the active acoustic applications that contribute to other EOVs as described above use specialized instruments engineered to make a specific targeted measurement of a variable unrelated to ocean sound. Rather than including all active acoustic methods in the Ocean Sound EOV, specific active acoustic sensors or techniques have been incorporated as needed into other EOVs. For example, acoustic Doppler current profilers are critical sensors for the Ocean Currents EOV. Acoustic transducers are also listed as potential future observing elements for the Subsurface Temperature EOV and acoustic sensors are similarly listed as future observing elements in the Zooplankton EOV.

There has been growing recognition that introduction of energy or chemical compounds for scientific observation can harm marine life, but users need guidance to make sure their proposed observations support the goal of healthy oceans. Even though Loew demonstrated in 1976 that short-term exposure to light can cause permanent degeneration of photoreceptors, underwater vehicles continued to use intense light sources to illuminate habitats in the deep ocean that were populated by animals whose vision was evolved for dim light in the deep sea.

Few worried about environmental impacts until high profile alarms were sounded by Herring et al. (1999). Similarly, even though it has been known for decades that manmade noise could mask communication of marine mammals (Payne and Webb 1971) and fish (Myrberg 1980), cause adverse reactions (Myrberg 1990), and even trigger lethal strandings of protected whale species (Frantzis 1998), many scientists who use intense sound sources to observe the oceans still do not understand the risk these pose to ocean health. If GOOS plans to include observation methods that add energy or chemical compounds to the oceans, then in order for it to maintain consistency with its goal of maintaining healthy oceans, it should establish a robust process to review any such methods to make sure that their use in GOOS involves negligible impacts on marine life.

Passive acoustic observations contributing to GOOS will be useful for long-term monitoring of climate change-induced alterations in the physical and biological components of marine environments, and will contribute to understanding trends in biodiversity, community composition, and distribution ranges of marine life. Unlike the highly specialized active acoustic systems, most passive acoustic recording systems measure the primary variables of sound pressure or particle motion in ways that are well suited for multiple uses, across a broad spectrum of sound frequencies. For example, nations have made major investments in acoustic observing systems to monitor human threats that produce sound in the ocean, including nuclear explosions, military sonar and ships. The benefit from incorporating data from these kinds of systems into an Ocean Sound EOV is demonstrated by the broad array of societal needs and scientific problems that have been addressed by CTBTO data, such as enhancing tsunami warning systems (Meier 2005), estimating the density and distribution of whales (Harris et al. 2018), documenting long-term changes in ocean noise (Miksis and Nichols 2016, Robinson et al. 2023), and relating changes in low-frequency sound to sea ice cover and wind speed (Robinson et al. 2019).

The Ocean Sound EOV as a cross-disciplinary EOV will provide a framework for passive acoustic observations that will advance our ability to understand changes in ocean sound over space and time, the sources that drive ocean soundscapes and the effects of anthropogenic sound on ocean ecosystems. Measuring this EOV will require coordination and standardization of observations that will advance our use of sound to understand the ocean, to understand the distribution and dynamics of ocean sound, how different sources of anthropogenic sound affect ambient ocean soundscapes, the effects of sound on marine life, and how acoustic monitoring can be used to assess biodiversity and ecosystem health.

## 1.4 How the Ocean Sound EOV contributes observations that address GOOS focus areas

GOOS has defined three core delivery areas into which observations can help society: (1) understand and manage changes to climate, (2) maintain ocean health, and (3) operational services that monitor threats and provide forecasts and warnings. Observations collected as part of the Ocean Sound EOV meet different requirements of these core delivery areas.

### 1.4.1 GOOS Focus 1: Climate

There are three abiotic consequences of climate change for which the Ocean Sound EOV provides important observations: severe storms, rainfall, and sea ice. Climate change increases the prevalence and severity of extreme weather events that have significant and increasingly grave consequences for human communities, on the coast and inland. Storms at sea generate strong winds, waves, and rain, which generate distinctive acoustic signatures (Nystuen et al. 2010; Yang et al. 2015; Riser et al. 2019). The Ocean Sound EOV aims to measure these signatures to better map normal variation in weather along with extreme events. Climate change is also affecting sea ice (Menze et al. 2017), glacier calving, and breakup of icebergs (Matsumoto et al. 2014). Acoustic monitoring is well suited to measuring changes in all of these ice-related features in real time over long time periods and over large areas across the Southern and Arctic oceans that are otherwise inaccessible. Climate change is affecting the distribution of marine life by altering abiotic features of habitat such as temperature, oxygen levels, and pH. Changes in the distribution of prey may cause changes in the distribution of predators and *vice versa*. The ability to track changes in the distribution of sound-producing animals over long spatial and time scales is an observation of the Ocean Sound EOV that is particularly important for hard-to-reach habitats that are impacted by a changing climate.

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### 1.4.2 GOOS Focus 2: Protect ocean health and support sustainable growth

An integrated approach to managing ecosystems requires mapping the distribution of environmental stressors and affected wildlife (Tyack et al. 2022). Effects depend upon the exposure of wildlife to each stressor. Estimating the effects therefore requires an ability to measure the distribution of stressor exposure among wildlife populations, and to model how these stressors and wildlife distributions will change as a function of natural changes and human actions, as well as how their effects on wildlife interact. Anthropogenic ocean sound has been recognized as a stressor to many forms of marine life. As a tool for studying the ocean and also as a way to monitor the stressor of anthropogenic sound, observations of ocean sound through the Ocean Sound EOV will provide information useful for ocean management by collecting observations that are not available through other EOVs. By identifying the sources of sound, soundscape analysts can monitor changes in anthropogenic, biotic, and abiotic natural sources of sound and how they change over time and space. Separating information about sound produced by wildlife from sounds produced by anthropogenic sources such as sonar, shipping and seismic surveys enables studies on the effects of human sound on wildlife (e.g., Moretti et al. 2014). These observations not only map sound as a stressor, but sounds made by soniferous marine organisms can also be observed using the remote sensing technique of passive acoustic monitoring to augment infrequent visual observation methods and provide continuous observations that may not be available from other techniques. Building upon earlier work in terrestrial ecosystems, marine bioacousticians are developing acoustic indices of biodiversity where visual estimates are difficult (Mooney et al. 2020). The Ocean Sound EOV will bring together observations of ocean sound already collected, coordinate those being collected and build capacity to increase the number and scale of relevant acoustical observations to monitor biodiversity and ocean health.

Increased acoustic monitoring can help quantify risks associated with changes in industrial activity in the ocean, such as changes in ship speed or routing (Dunn et al. 2021). It has also documented the effects of changes in shipping that took place during the COVID-19 pandemic (Basan et al. 2021; De Clippele and Risch 2021; Gabriele et al. 2021). There are some areas where noise from coastal development and recreation is thought to have played a role in habitat degradation and the loss of important species (Tyack 2008). Hydrophones deployed in coastal and offshore areas can observe changes in these sources of sound. GOOS monitoring will be essential for documenting changes in soundscapes associated with coastal development and understanding the relationships between anthropogenic ocean sound and ecological changes.

### 1.4.3 GOOS Focus 3: Operational services that monitor threats and provide forecasts and warnings

Mapping natural sources of sound in the ocean provides operational information on vulnerable species and on important threats such as tsunamis and severe storms as discussed in section 1.4.1. Underwater earthquakes can generate dangerous tsunamis, so seismic monitoring can help provide early warning for tsunami risk. Ocean bottom seismometers typically measure both sound pressure and acceleration. Early warning systems require capabilities for near real-time transmission of events to shore. A critical feature for warning systems is that they must provide the warning in time to take protective actions, within a few hours for tsunamis that may travel at hundreds of km/h (An and Liu 2014). This can be achieved by cabled systems or buoys with rapid telemetry to shore stations. The expense of cabled systems limits their coverage, but recent developments of distributed acoustic sensing offer the potential to use existing undersea fiber optic cables to detect and localize earthquakes (Zhan 2019). Thus, acoustic measurements of natural sources of ocean sound provide operational services of great importance for monitoring and forecasting ocean hazards.

Real-time acoustic monitoring of whale calls is used by some operational systems that warn ships of whale presence (Spaulding et al. 2009). These systems use arrays of buoys with hydrophones moored in locations that can monitor for right whales near shipping lanes. Electronics on board the buoy detect signals that could be right whale calls. Extracts of sound judged by the detector to be whale calls are transmitted on a regular schedule to shore where a team of bioacousticians can validate the calls. Once a validated call indicates the presence of whales, this information can be sent within hours for notifications to mariners establishing zones mandating slow vessel speeds and alerting mariners to reduce the risk of collision (https://www.fisheries.noaa.gov/feature-story/help-endangered-whales-slow-down-slow-zones).

Soundscape model data are beginning to be applied to assist in managing the cumulative effects of multiple ocean uses of areas requiring special protection (Haver et al. 2018, Prawirasasra et al. 2021). Due to the complexity of propagation modelling, these soundscape models must be validated with *in situ* data that should be made transparently available for review through GOOS and the Ocean Sound EOV.

# 2 MEASUREMENTS AND DERIVED DATA PRODUCTS REQUIRED TO MEET OCEAN SOUND EOV GOALS

The requirements for acoustic measurements and derived data products can be specified and matched to needs from each of the 3 GOOS primary goals that can be answered by observations collected through the Ocean Sound EOV. Figure 2.1 illustrates the information flow from recordings of primary sound variables to calibrated measurements of the sub-variables of sound and supporting variables as identified in the EOV specification sheet (Ocean Sound EOV specification sheet) to derived data products that provide ocean observations to address the 3 GOOS primary goals.

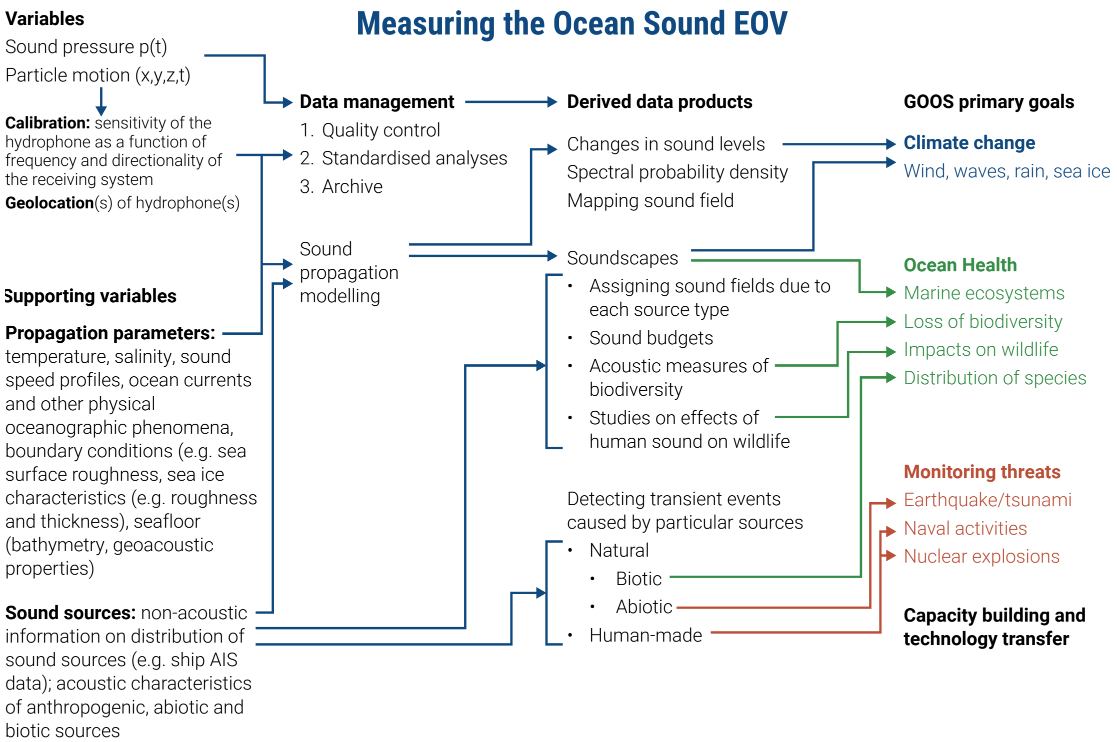



Figure 2.1 Use of ocean sound measurements combined with measurements of supporting variables and modeling leads to derived data products that support the three primary themes of GOOS: climate change, ocean health and monitoring threats.

## 2.1 Primary ocean sound variables: Sound pressure and particle motion

Sound pressure and particle motion are the two primary variables in the specification sheet for the Ocean Sound EOV. Sound propagates through water as compressions and expansions (sound pressure) as particles oscillate back and forth (particle motion). A variety of instruments are currently used to record these parameters. The mammalian ear detects the pressure component of sound, and the primary electronic sensor used for underwater sound is the hydrophone, which also measures changes in pressure induced by sound. Fish and invertebrates detect particle motion with sensory organs (e.g., lateral lines, otolith, statocyst) that function as accelerometers (Popper and Hawkins 2018). The particle motion component of sound can be described as displacement (m), velocity (m/s), and acceleration ($m/s^2$) of particles (vector variables). Particle motion needs to be quantified in all studies that investigate sounds for which fish and aquatic invertebrates are the relevant receivers, as it is the primary, and sometimes only, acoustic signal that these animals detect. Particle motion can be predicted from sound pressure levels collected by hydrophones under most conditions. However, due to the complex relationship between pressure and particle motion in certain conditions, it should be measured directly to describe soundscapes near the sea surface and seafloor, in shallow water and close to sound sources; these observations can be collected via the use of a number of instruments (see below). Nedelec et al. (2021) provide software for determining when particle motion should be directly measured, rather than calculated from pressure measurements. Measuring both sound pressure levels and particle motion can answer questions about how each contributes to soundscapes, and the direction and potentially the distance to sound sources (Matias and Harris 2015).

Particle motion detectors are a newer technology than hydrophones and as a result have not been deployed as widely. Particle motion can be measured by three methods: (1) by measuring the pressure gradient between two hydrophones (Zeddies et al. 2010), (2) directly measuring with sound-induced velocity sensors, and (3) via the use of accelerometers (Nedelec et al. 2021). Hydrophones for measuring pressure gradients must make accurate phase measurements, a capability that tends to be costly, while particle velocity sensors often are only useful for frequencies below several tens of Hz. Measuring acceleration is usually better for measuring particle motion induced by higher frequency sounds. Accelerometer measurements also provide directional information on sound sources and can be deployed on moorings and floats. Further development of particle motion detectors and methods for deploying them will facilitate measurement of this component of ocean sound in observation systems.

Hydrophones convert acoustic pressure into a voltage that can be amplified, filtered, digitized and recorded by electronic systems. Hydrophones and digital recording systems can be designed to be small and to draw relatively little power, so are well suited to being added to many components of observing systems. When a hydrophone is calibrated, the voltage response is measured as a function of frequency and often as a function of the horizontal and vertical angle. In cases where the hydrophone is omnidirectional for the frequency band of interest, the calibration allows conversion of hydrophone outputs to the standard SI units of pressure, Pascals, as a function of frequency, ignoring directivity. By contrast, particle motion induced by sound is directional, leading to a vector quantity that includes orientation as well as magnitude. While hydrophones are relatively small and low power, the high data rates of some acoustic recordings can provide challenges for the data storage and transmission capabilities of some ocean observing systems. Most of the derived data products of the Ocean Sound EOV require the recording system to be calibrated in SI units of pressure (Pascal), displacement (m), velocity (m/s) or acceleration ($m/s^2$).

## 2.2 Derived data products for the Ocean Sound EOV

Some ocean sound data products can be derived directly from an acoustic pressure time series from one acoustic sensor. Others require a network of acoustic sensors. Mapping sound fields requires propagation modeling often supplemented by measurements of ocean sound, and soundscapes require information about sound sources as well. The derived data products involving calibrated sound measurements, spectral probability densities, sound propagation models, sound field maps, soundscapes and associated supporting variables and transient events are discussed here in order of increasing complexity and requiring more supporting variables.

### 2.2.1 Long-term changes in sound levels

Calibrated measurements of sound at sentinel sites over long time periods allow for the analysis of changes in levels at different frequencies in the local sound field over time, and establishing trends has been used to anticipate future changes. Well-calibrated recordings from the same site can provide important data on changes in ocean sound over time at the site and can be combined with observations from other sites to provide greater context on spatial variability. However, there are few published data on the trends of ocean sound, and how and where sound levels are changing, making most attempts to regulate ocean sound highly precautionary and lacking adaptability to any change. There are no global or regional acoustic analogs to the Keeling Curve for atmospheric carbon dioxide (Keeling et al. 1976). Andrew et al. (2002) reviewed data from the 1960s and 1990s from hydrophones at one site off Point Sur, California and reported an increase of 10 dB in a low-frequency band likely dominated by shipping noise. This led to the conclusion that ocean sound is increasing at about 3 dB/decade and predictions that steadily increasing levels of sound may increase stress on marine life globally. However, Andrew et al. (2011) show a slowing rate of increase more recently at this site and Miksis and Nichols (2016) show that ocean sound is decreasing at other sites, which highlights the limitations of extrapolation from one time period to another and from one site to larger spatial scales. Understanding changes in ocean sound at larger scales of time and space clearly requires much more extensive sampling of long-term changes in sound than has been achieved in the past.

Trends in ocean sound also depend upon the frequency band of sound observed. Requirements to standardize the baseline reporting of measurements of underwater ambient sound are being developed by the International Organization for Standardization as ISO/CD 7605. It will be important for ocean acoustic observations to follow this standard as a baseline requirement once it is published. Selection of the frequency band(s) to be studied for specific ocean acoustic observations depends on the specific research question and management objectives for which the observations are needed. Important frequencies could include those that are important for monitoring physical processes, those at which marine species communicate, frequencies needed to monitor human activities such as around industrial sites or protected areas, etc. The importance of different frequencies also depends upon physical properties of how sound propagates in the ocean and on situations where human sound in a frequency band masks acoustic signals used by marine animals to communicate, orient, and find and capture prey. For example, sounds at frequencies below a few hundred Hz can propagate with little loss in deep oceans, with large whales using these frequencies to produce sounds that are detectable hundreds of km away. Low-frequency sound from ships propagates equally well, so that the added sound from ships elevates inputs of noise in low-frequency bands used by whales, adding to soundscapes and potentially obscuring sounds generated by whales for communication (i.e., the ship noise "masks" the whale calls). Another frequency band that is important in terms of effects on marine life is the 1-10 kHz range. Mid-frequency naval sonars that operate in this band can trigger lethal disturbance responses in beaked whales (de Quirós et al. 2019). However, managing these kinds of effects demands knowledge of levels of exposure of wildlife to sound within the relevant frequency bands, which is often lacking (e.g., Brownlow et al. 2019).

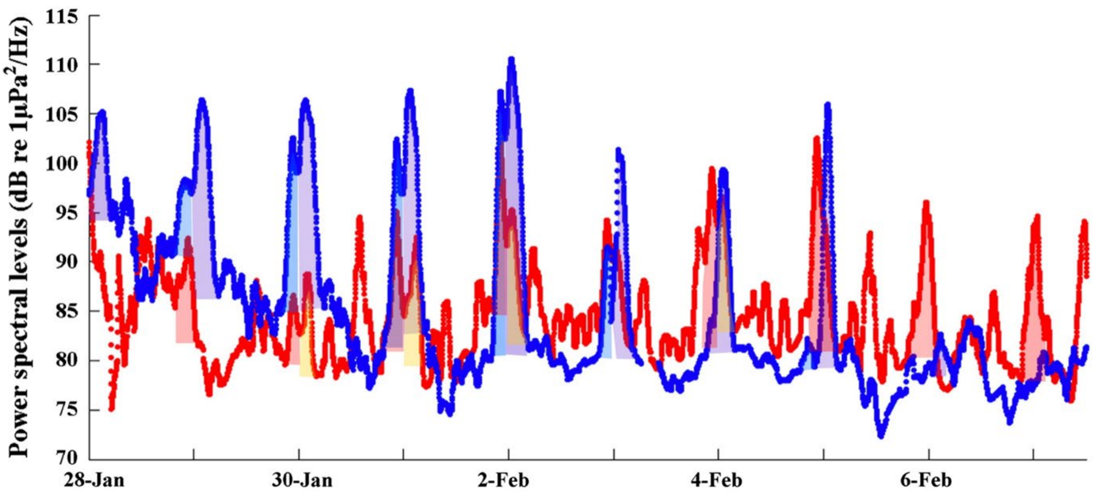



Figure 2.2. Diurnal variation in sound from fish choruses recorded inshore (blue) and offshore (red) sampling sites off Port Hedland, Western Australia (Parsons et al. 2017). Reprinted by permission of Taylor & Francis Ltd, http://www.tandfonline.com.

Sampling strategies to characterize long-term trends in ocean sound must account for high levels of variability over shorter time scales. In many ocean areas, strong diurnal and seasonal changes in ocean sound are caused by variation in biotic and abiotic sources of sound, and in abiotic variables that affect sound propagation. For example, Figure 2.2 shows the amount of acoustic power in the 50-2000 Hz frequency band for inshore (blue) and offshore (red) sampling sites off Port Hedland, Western Australia (Parsons et al. 2017). In addition to the strong diurnal pattern, note how the inshore site starts with higher peaks than offshore at the start of the 10-day sample, with offshore peaks becoming stronger, throughout the sample. On a much longer time scale, Figure 2.3 shows median values of ocean sound in the 40-60 Hz range from offshore of Cape Leeuwin in the southwest of Australia. Note the pronounced seasonal variation in sound pressure levels (SPL) coupled with a clear long-term decline at this site. These seasonal sources of variability must be accounted for if long-term estimates are to be robust.

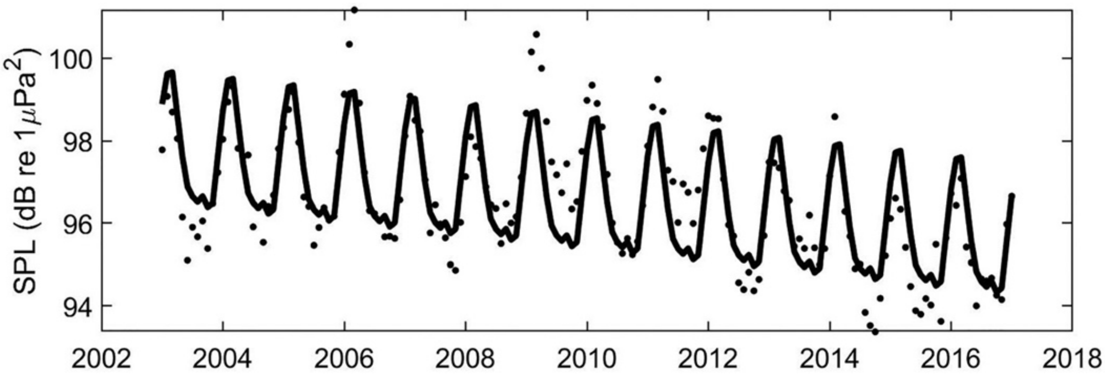
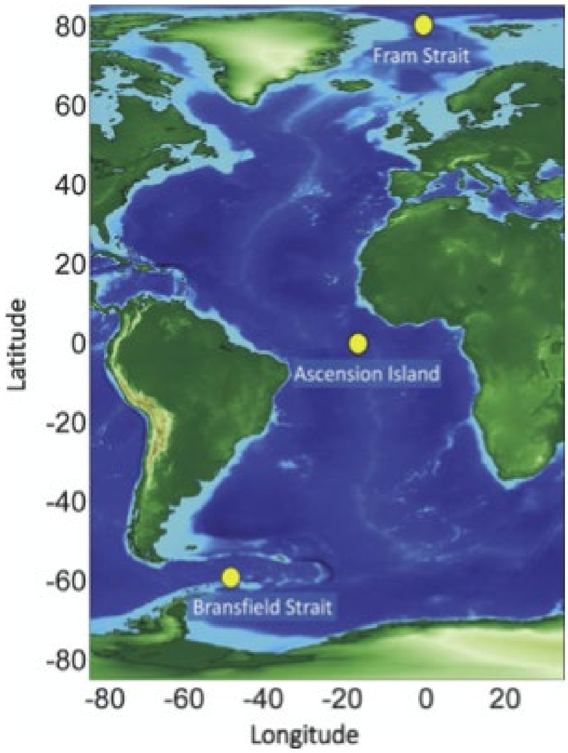



Figure 2.3 Median values for ocean sound in the 40-60 Hz frequency band from a hydrophone close to Cape Leeuwin, Australia aggregated for each month from 2003 to 2017. Reproduced from Harris et al. (2019), with the permission of the Acoustical Society of America.

### 2.2.2 Spectral probability density

Spectral probability density provides statistics of how sound pressure level varies for each frequency of sound in a large sample (Curtis et al. 1999, Merchant et al. 2013). Spectral probability densities have a variety of important applications. They provide input data for algorithms that use data on energy at different frequencies to estimate what sounds have been produced by vocal animals and which sounds are generated by abiotic processes such as wind and rain. Archiving of these data enables reanalyses that in the future can test more refined algorithms to provide more accurate hindcasting of these sources of sound. Understanding levels of ambient sound at different frequencies is also critical for those who plan to use sound in the sea because this provides the noise data required for calculating signal-to-noise ratios that are important for predicting the performance of passive and active acoustic systems. Spectral probability density data allow one to compare the level of noise over the same frequency range as the signal of interest. For example, the performance of passive systems that listen for sources of sound such as ships, earthquakes, explosions, or animals, and of active systems that listen for echoes from submarines, marine life, the seafloor or geological strata below the seafloor, all depend upon the signal-to-noise ratio for detecting the signal of interest within the ambient sound that occurs in the same frequency band. These systems are critical for scientific research, national security, and economic activities valued at tens of billions of dollars annually. The sounds produced by marine animals and the sensitivity of their hearing varies over frequency, so interpreting the effects of noise on their own use of sound requires comparing the spectral distribution of their own sounds and hearing to that of the noise.

The distribution of ocean sound energy can be estimated as a function of frequency by calculating the spectrum of segments of a fixed time interval, such as 1 minute. Digital signal processing can transform the pressure time series into an estimate of the amount of energy at each frequency, called the spectrum of the sample. For a large sample of spectra, the distribution can be plotted as a spectral probability density. Figure 2.4 from Haver et al. (2017) shows such plots calculated from 200s time intervals for frequencies between 15 and 100 Hz recorded over 16 months at sites in the Arctic, at the Equator, and the Antarctic, where the Arctic plot labels 5%, 50%, and 95% contours. There is more variability in the polar sites, with periods of lower sound levels in the polar sites coinciding with sea ice cover and fewer whale calls. High levels of oil and gas exploration year-round led to consistently higher overall levels at the equatorial site.



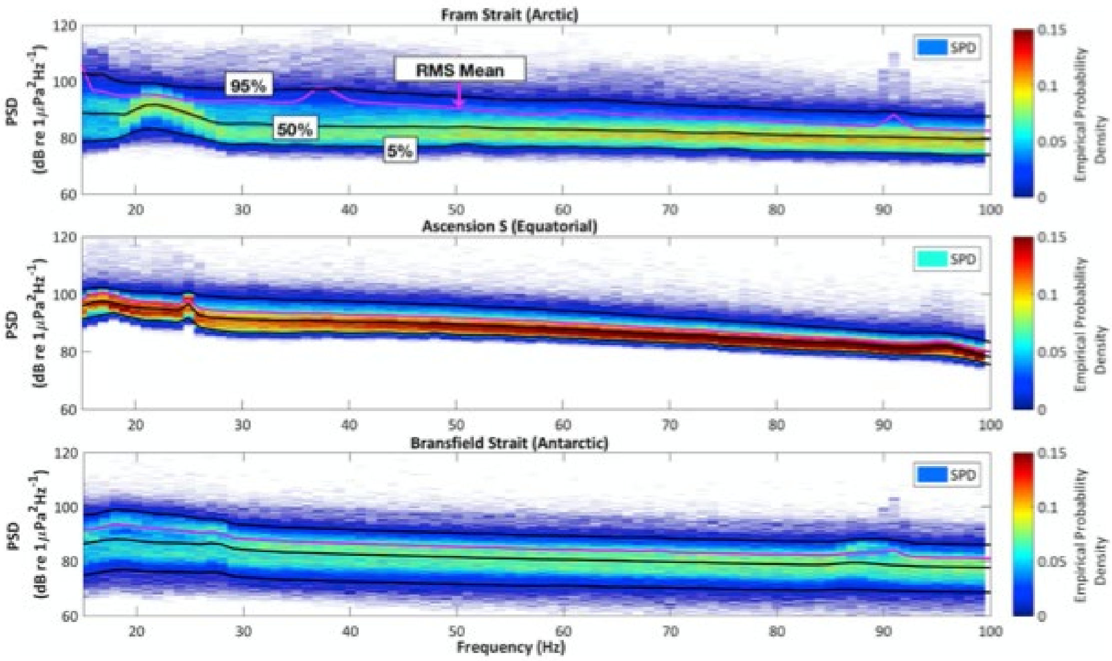




Figure 2.4 Spectral probability density plots of 200s intervals of ocean sound in 1 Hz bins across the 15-100 Hz band from Arctic, Equatorial and Antarctic sites (from Figures 3 and 7 of Haver et al. 2017). Creative Commons (CC BY-NC-ND 4.0).

### 2.2.3 Using sound propagation modeling and supporting variables to map the sound field

Figure 2.1 shows that derived data products that map the sound field and spatial mapping of soundscapes both require the use of sound propagation modeling which, in turn, requires supporting variables on propagation and sound sources. Sound propagation models are highly useful for navies and ocean-going commercial activities such as seismic surveys. As a result, this is a very well-developed area, with many software packages making models available. The ocean acoustics library OALIB (https://oalib-acoustics.org) contains downloadable software used to model sound propagation in the ocean. However, the accuracy of model outputs depends upon accurate and precise characterization of the properties of the environment that affect sound propagation. These include properties of the ocean itself – temperature, salinity, sound speed profiles, ocean currents and other physical oceanographic phenomena – to be sampled in enough detail over the area to be modelled. It also depends on conditions at the boundaries of the ocean – characteristics of the sea surface such as wave-induced roughness and of the seafloor such as bathymetry and geoacoustic properties. There are well-established databases for use with sound propagation models, which can be supplemented by *in situ* data collected along with the acoustic data, as necessary. In some areas, seafloor characteristics that affect propagation of sound can change significantly across small spatial scales (10s – 100s of m).

If the propagation conditions are characterized adequately across a spatial area, the sound field can be estimated based upon propagation modelling and acoustic information about sound sources. The sound field is usually defined as the distribution of sound pressure as a function of three-dimensional location and time, P(x,y,z,t). This adds a spatial component to the sound observations whose changes over time and frequency are defined by the spectral probability density. Mapping of sound fields (e.g., Figure 2.5 for a two-dimensional plot of depth vs horizontal distance) requires modelling of sound propagation in the ocean using propagation parameters as supporting variables. Measurements of ocean sound in appropriate recording sites can be compared to output of modelling of sound propagation throughout wider ocean areas to verify the predictions of these models. Ideally, measurements and modelling are combined to provide a ground-truthed estimate. For example, Figure 2.5 shows an estimate of the sound field generated by an underwater volcanic eruption as measured by a glider whose sawtooth path is indicated by the black dotted lines, with the sound field estimated using a range-dependent propagation loss model.

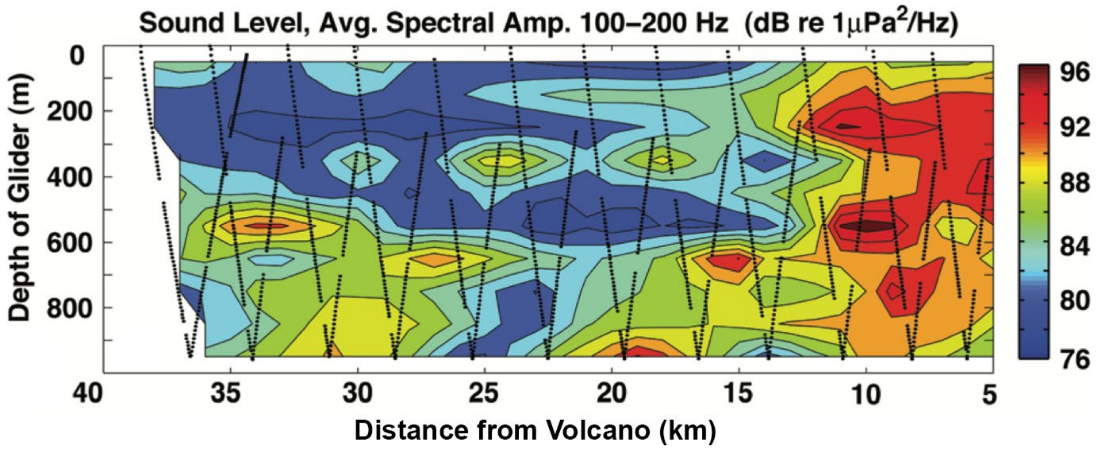



Figure 2.5 Sound field generated by an underwater volcanic eruption as measured by a glider whose sawtooth path is indicated by the black dotted lines, with the sound field estimated using a range-dependent propagation loss model. Reproduced from Matsumoto et al. (2011), with the permission of the Acoustical Society of America.

Modeling the soundscape requires estimating the contribution to the sound field made by each sound source. This requires a new set of supporting variables describing acoustic and non-acoustic (e.g., three-dimensional location) characteristics of each relevant sound source. Figure 2.6 uses a propagation model to estimate the sound field from four sources of sound averaged over a nominal 2-year period in the Dutch North Sea. In this example, data on the distribution of all of these sound sources was not available for one 2-year period, so Sertlek et. al. (2019) constructed a fictional 2-year scenario by combining data on wind and explosions from 2010 to 2011, on shipping from 2014, and on seismic surveys from 2007 to 2008. Modeling how sound from intense anthropogenic sources of sound propagate in a particular environment can be used to estimate the risk of impact on marine life from different sound sources. Comparing the sound field estimated for all sources on the right of Figure 2.6 with that from each individual sound source shows that the sound field is dominated by shipping at this frequency. It is important to verify sound fields predicted from sources such as shipping (e.g., Putland et al. 2022 for shipping in the North Sea).

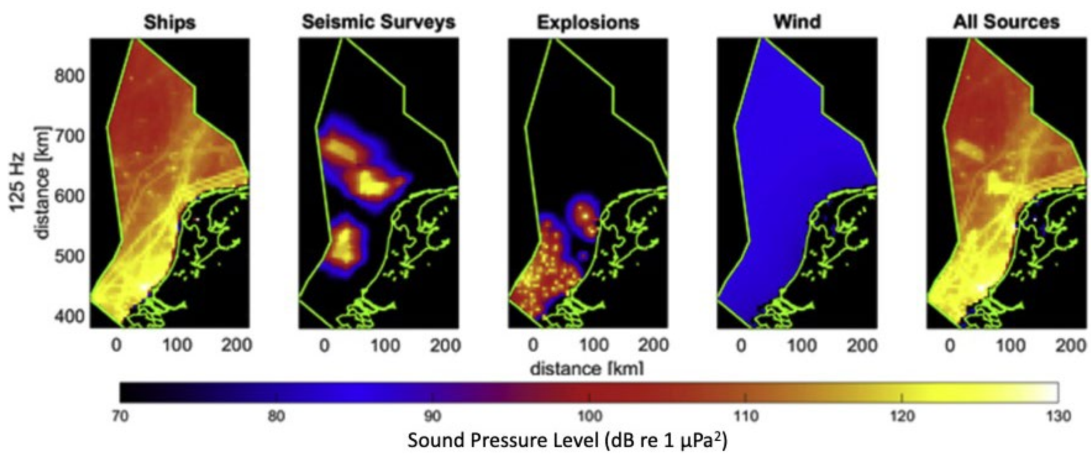



Figure 2.6 Sound pressure levels at 125 Hz averaged over a nominal 2-year period from ships, seismic surveys, explosions, wind and all of these sources in the Dutch North Sea (Sertlek et al. 2019). The squared sound pressure is averaged over all receiver depths for each location. Creative Commons (CC BY 4.0).

### 2.2.4 Supporting variables on sound sources to define soundscapes and classify ocean sounds

Information about the acoustic characteristics of sound sources and about their distribution in time and space is essential for understanding soundscapes and for detecting acoustic events caused by sound sources (see arrows from sound source box on lower left of Figure 2.1). Many transient underwater sounds are caused by humans, abiotic events such as earthquakes, and by marine animals. Much of the work conducted on ocean acoustics has traditionally been funded by military organizations seeking to detect and track ships and submarines; subsequently many of the major ocean acoustic observing systems have been implemented to detect these ships and various geological phenomena such as earthquakes. The significant investment in systems to detect the sounds produced by different kinds of ships has driven extensive efforts to characterize sources of ocean sound. For example, MacGillivray and de Jong (2021) describe a model they have developed and validated to use data from the Automated Information System (AIS) to predict ship source level spectra.

An important task for ocean acousticians has also involved identifying sounds produced by different natural sources of sound. Unlike human sources, whose acoustic properties can be studied by operating the source, acousticians must identify the source of most natural sounds. If the event has a distinctive signature, acousticians can detect, classify, and locate it. The first decades of marine bioacoustics were devoted to identifying what species of animal produced what kind of sound. The source of some transient sounds in the ocean has been a persistent mystery. For example, Wenz (1964) reported a "boing" sound recorded by the U.S. Navy in the North Pacific Ocean. Tracking of these sounds off Hawaii led Thompson and Friedl (1982) to speculate that the source was a whale, but it was not until Rankin and Barlow (2005) used a hydrophone array towed from a ship to locate these "boing" sounds and then approached the source that it was confirmed to be minke whales. These efforts mean that we have extensive data on the acoustic signatures of different species of marine animal. However, significant efforts will be required to develop and validate open-access databases on the sound sources.

Sound source information that is critical for soundscapes includes acoustic information about each source: how the source emits sound in terms of the three-dimensional beam pattern as a function of frequency and time. Given this information about the acoustic characteristics of each sound source and the location of each source, propagation modelling can be used to predict the sound field generated for each source. For example, Figure 2.7 shows the sound field predicted for an omnidirectional sound source operating at 600 Hz with a source level of 220 dB re 1 μPa m in the Gulf of Mexico (DeRuiter et al. 2006). Decreasing sound speed at depths below about 50 m causes sound to refract downwards and then reflect off the seafloor, with a shallow (<50 m) surface duct for sound. This plot is generated by a propagation model only using information from the supporting variables on the sound source and propagation parameters.

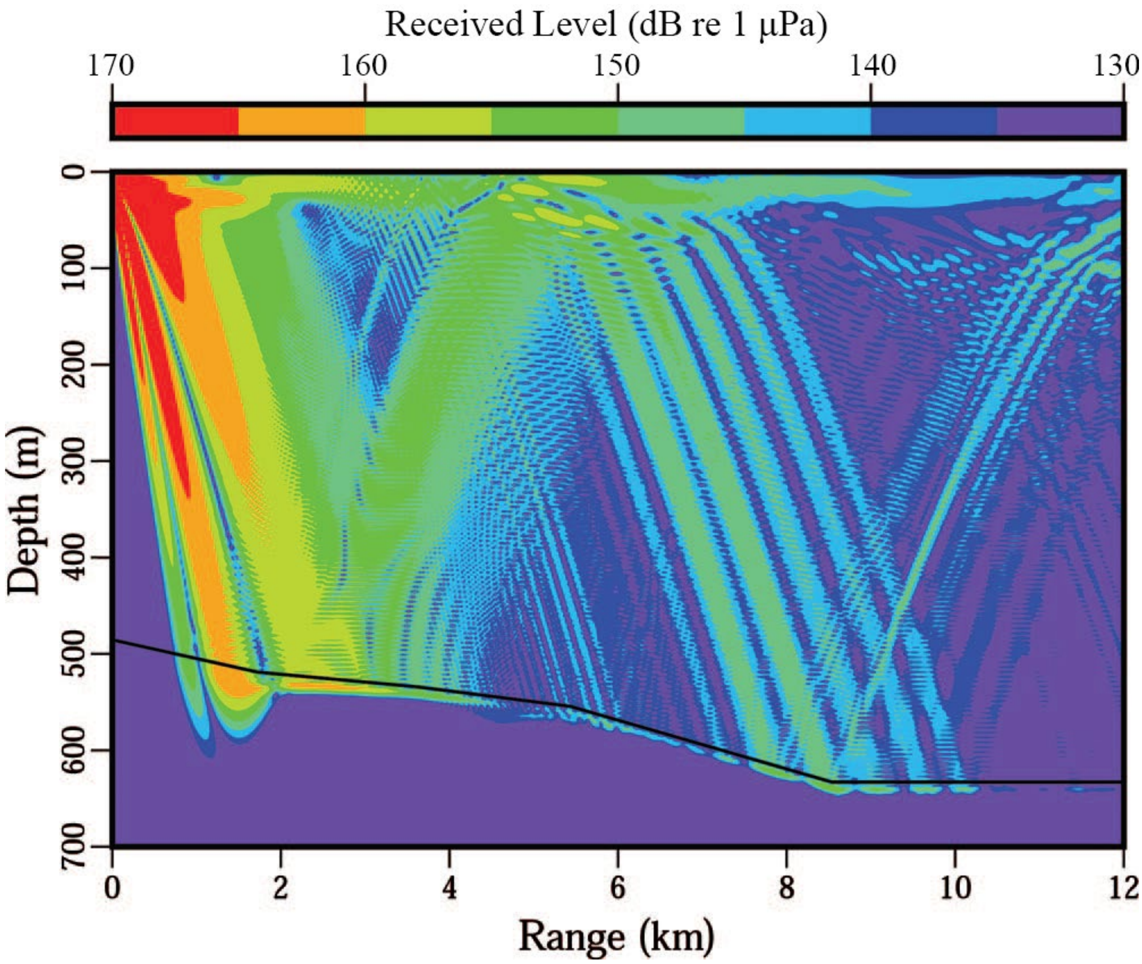



Figure 2.7. Estimated sound field generated by an omnidirectional sound source operating at 600 Hz with a source level of 220 dB re 1 µPa m in the Gulf of Mexico. Reproduced from DeRuiter et al. (2006), with the permission of the Acoustical Society of America.

### 2.2.5 Soundscapes

#### 2.2.5.1 Assigning sound fields due to each source type

The difference between a *sound field* and a *soundscape* is that a receiver characterizing the *soundscape* uses information about sound sources to analyze how different sources contribute to acoustic observations. Modelling of the *sound field* estimates sound pressure at each location and time, using propagation models and models or data of the sound source levels of all relevant sources. A first step in analyzing the soundscape derived from acoustic observations involves estimating the sound fields produced by each source type, which also requires supporting variables on sound sources and propagation parameters. Once the acoustic characteristics of sound sources in the ocean have been identified, it becomes possible to identify which sound sources contribute to which elements of the spectral probability density. For example, Figure 2.8 indicates the peaks around 20 Hz due to calls of blue and fin whales, the broader and overlapping 10-100 Hz sound from ships, and a separate peak at 1000 Hz from fish choruses.

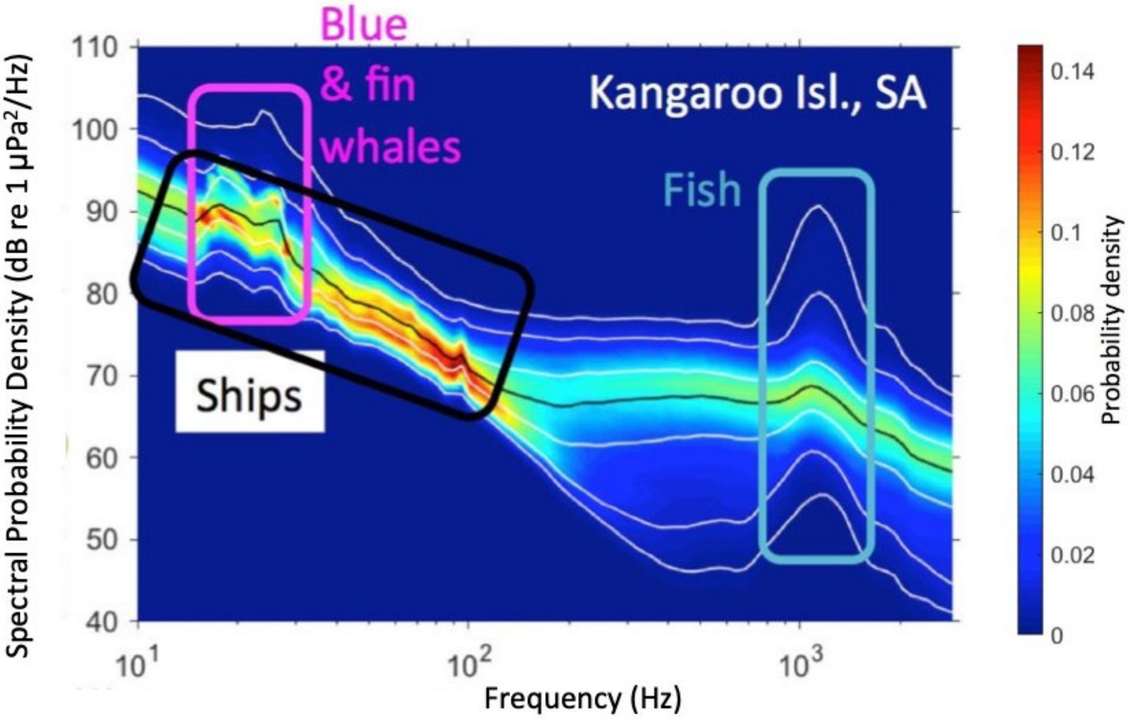



Figure 2.8 Spectral probability density plot from Kangaroo Island, South Australia, that indicates signals from blue and fin whales, ships and fish (Erbe et al. 2016). The white lines indicate the 1, 5, 25, 75, 95 and 99th percentiles of spectral probability density, and the black line indicates the median. Used with permission from Christine Erbe.

Ideally, observations that assign sound fields to sound sources go beyond indicating spectral peaks at one site and involve modeling the propagation of sound from the estimated distribution and acoustic characteristics of each source (as illustrated in Figure 2.7 for a 600 Hz source and as illustrated for several sound source types in Figure 2.6) and then comparing these predictions to measurements of the sound field from judiciously located hydrophones (e.g., Putland et al. 2022 for shipping). The development of ocean soundscapes that estimate levels of sound sources and propagation loss to receivers can help test hypotheses about how changes in sources of sound affect the sound field. For example, Figure 2.9 shows that sound levels at this site off southwest Australia were highest when the Antarctic ice volume was lowest, suggesting that ice coverage and sea surface temperature may affect the sources of sound and/or sound propagation (Robinson et al. 2019). Developing models that accurately predict changes in soundscapes as a function of human activities or natural factors would be extremely valuable to users and managers of ocean sound (see also Section 2.2.5.3). Larger scale models that include several sources of sound might not be a feasible product of the Ocean Sound EOV in the short term, but may become possible after developing greater understanding of how global and ocean basin-scale soundscapes are affected by human activities and natural biotic and abiotic factors such as season and climate mode.

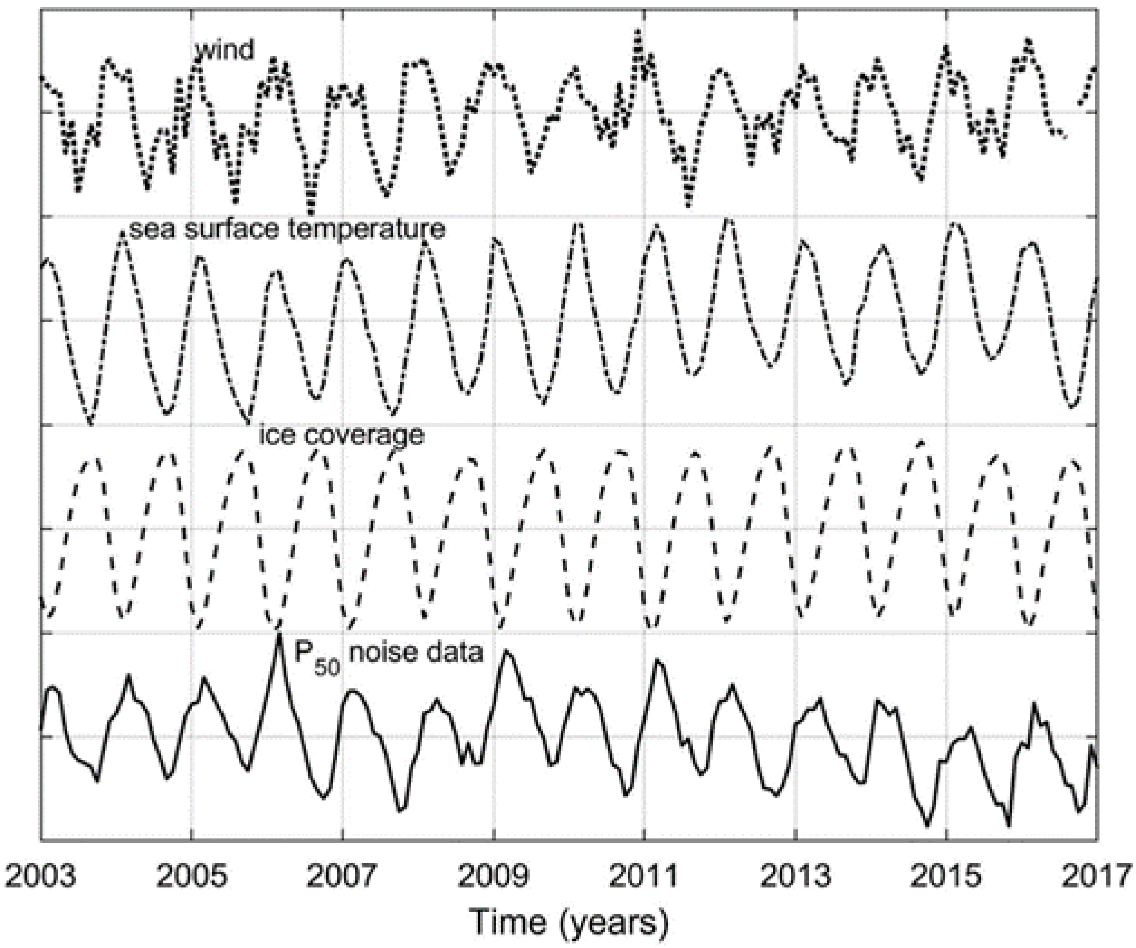



Figure 2.9. Comparisons of wind speed, sea surface temperature and ice coverage from areas near a hydrophone located 1 km deep offshore of Cape Leeuwin off the southwest coast of Australia whose median (P50) noise data are indicated on the bottom waveform. From Robinson et al. (2019). Contains public sector information licensed under the Open Government Licence v3.0.

### 2.2.5.2 Sound budgets

Sound budgets estimate how much of the sound energy at each frequency for a defined time and space derives from each of the relevant sources of sound. Defining a sound budget requires supporting variables about the sound sources as indicated on the bottom left of Figure 2.1. Efforts to manage the impacts of elevated sound levels on marine ecosystems demand understanding the sources of these elevated levels. Sound budgets help managers and stakeholders to predict the effects of current and planned activities on ocean sound fields and to understand how changing the number and distribution of sources can reduce the negative impacts of sound on marine ecosystems. Tracking changes in sound budgets over time makes it possible to estimate how different sound sources contribute to changes in ocean sound through time.

If we know the acoustic energy emitted by all of the sources of each important type in an area, and if we have measured the aggregate sound field in that area, we can estimate a sound budget in terms of acoustic energy or the percentage of sound in a given frequency band that is produced by the source relative to the measured sound level from all sources. For example, Figure 2.10 shows the cumulative probability distribution of sound energy in Admiralty Inlet, Puget Sound, Washington, USA, in the 20-30,000 Hz band over an entire year, as measured (black line), and estimated based on Automatic Identification System (AIS) data from ships that passed by this area (gray zone) (Bassett et al. 2012). Source levels for each type of ship were estimated by coordinating acoustic data with passage of ships documented by AIS. Figure 2.10 shows a good agreement between the measured acoustic data and estimates based upon the model for vessels, except during the quietest periods below 110 dB re 1 µPa. This agreement suggests that most of the sound energy recorded at this site was produced by AIS-equipped vessels, which were present in the area 90% of the time.

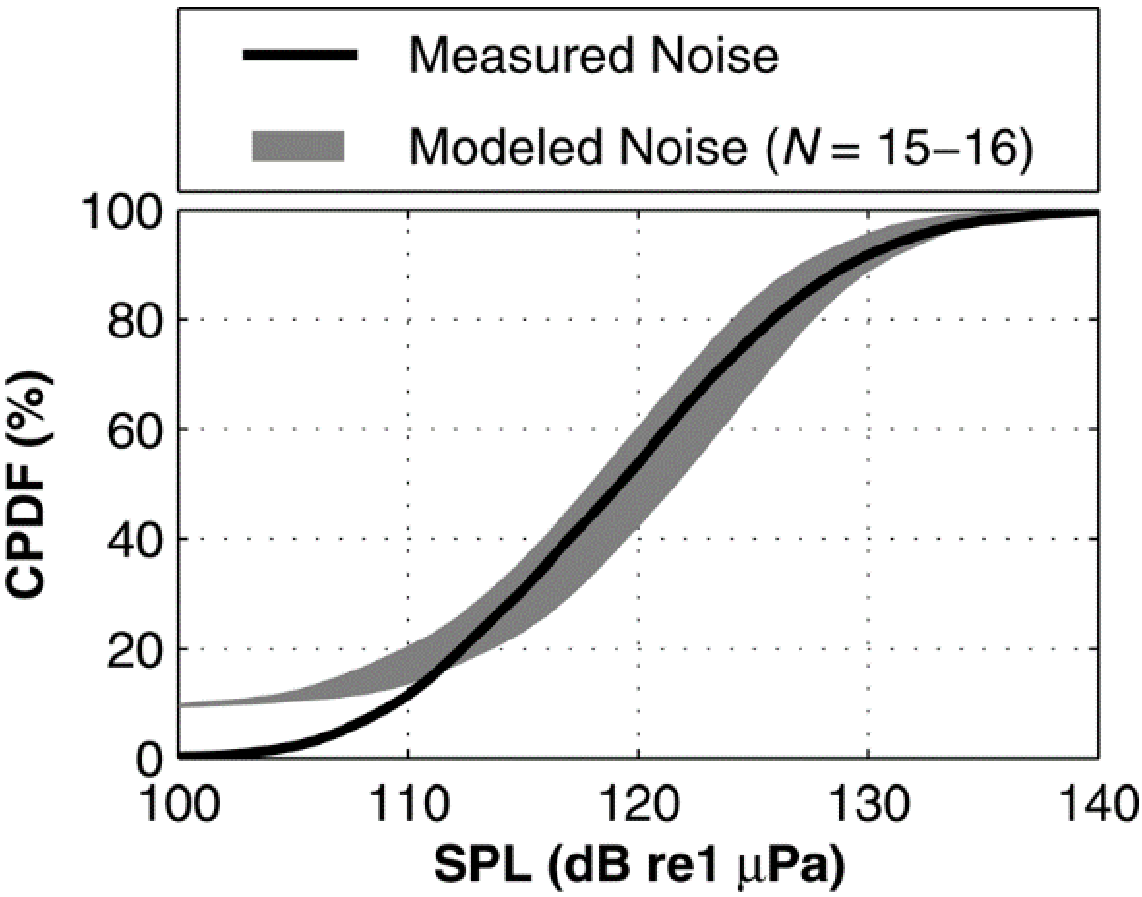



Figure 2.10 Cumulative probability distribution of sound energy in the 20-30000 Hz band as recorded during one year in Admiralty Inlet (Bassett et al. 2012). The grey area represents the distribution predicted by the model based on propagation modelling of known vessel passages, and the black line indicates the measured distribution. Permission for re-use granted by the Acoustical Society of America.

Table 2.1. Sound budget for Admiralty Inlet in the 20-30,000 Hz band from 7 May 2010 to 9 May 2011. Vessels comprise the main sources of ocean sound here, and the table breaks down the contribution of each class and type of vessel. Modified from Table V of Bassett et al. 2012. Permission for re-use granted by the Acoustical Society of America.

| Vessel Class | Vessel Type | Energy (MJ) | % of Budget |
|---|---|---|---|
| Commercial | Container | 249 | 57 |
| | Bulk Carrier | 71 | 16 |
| | Tug | 40 | 9 |
| | Vehicle Carrier | 18 | 4 |
| | General Cargo | 9 | 2 |
| | Oil/Chemical Tanker | 9 | 2 |
| | Fishing | 1 | <1 |
| Passenger | Ferry | 23 | 5 |
| | Cruise | 16 | 4 |
| | Other | <1 | <1 |
| Other | | 1 | <1 |
| Total | | 438 | 100 |

Table 2.1 lists the total amount of acoustic energy in megaJoules (MJ) and percentage of the sound budget during this year in Admiralty Inlet produced by the different classes of vessel identified via AIS. These estimates are important for estimating the impact of adding sound energy from existing and proposed human sources, and for estimating the reduction of sound energy that would result from reducing or moving sound sources, for example, to protect vulnerable wildlife or ecosystems. In this case, commercial vessels were responsible for over 90% of the energy and over half of the overall energy came from container vessels. If a population were considered to be threatened by noise in this area, then management would need to focus on reducing risk from the major sound sources, while devoting less effort to reducing sound energy from minor noise sources. The sound budget can help to identify sound sources whose reduction will be most effective in reducing noise. However, predicted effects will differ for different sites with different human activities and populations that may be sensitive to different frequencies of sound. For example, Southall et al. (2019) propose criteria for risk of adverse effects on the hearing of marine mammals that include peak pressure levels to account for effects of intense pulses and maximum sound exposure levels that integrate sound energy weighted by a function related to animal hearing over a specific time interval. While comparing the total energy produced by different sources of sound over a year or more can help prioritizing major and minor sources, most analyses of effects of sound on wildlife focus on sound pressure levels or sound exposure levels measured over time periods shorter than a day, durations that are more relevant to wildlife. Managers interested in reducing effects will usually focus on these criteria rather than long-term averages.

### 2.2.5.3 Estimating effect of changing human activities on ocean sound

Once one understands the acoustic signatures of different sound sources and can model how sound propagates in the ocean, it becomes possible to model the effect of proposed changes in human activities on the ocean soundscape in affected areas. For example, Aulanier et al. (2017) modeled the effect of increasing shipping traffic on ocean soundscapes in the Canadian Arctic, where climate change is opening up new shipping routes. Figure 2.11 shows the percentage of time when shipping noise in the 1/3 octave band centered on 63 Hz is expected to exceed ambient noise in Lancaster Sound if there are ten times more ships (right cell) than current traffic (left cell). For animals that have hearing sensitive enough to hear the ambient noise level, then times when shipping noise exceeds ambient indicate the onset of risk that the shipping noise may induce stress, disturb normal behavior, or mask other relevant signals, such as sounds of predators or calling conspecifics.

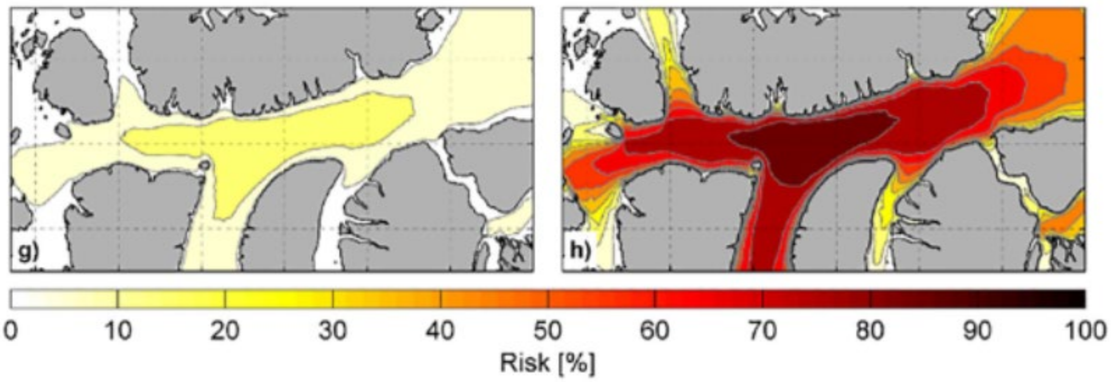



Figure 2.11. Percent of time when shipping noise in the 1/3 octave band centered on 63 Hz is expected to exceed ambient noise in Lancaster Sound if there are ten times more ships (right cell) than current traffic (left cell). Copyright (Aulanier et al. 2017), with permission from Elsevier.

Different marine species have different sensitivities to sound at different frequencies, which means that different species will experience the loudness of sounds in different ways. Figure 2.12 show the audiogram, or plot of hearing threshold against frequency, for 6 marine mammal species, and a rough estimate of frequency-specific hearing for baleen whales, which specialize in low-frequency communication (Erbe et al. 2014).

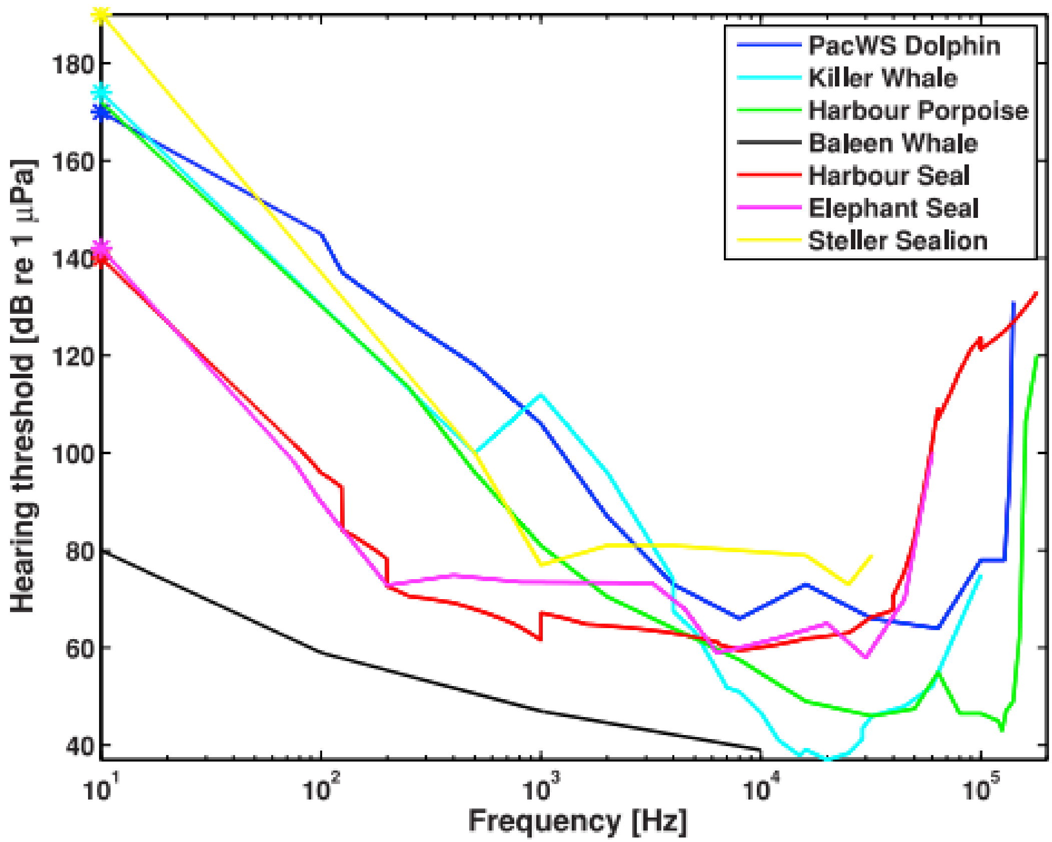



Figure 2.12. Audiograms of 6 marine mammal species found in the waters of British Columbia, Canada, and an estimate of hearing thresholds for baleen whales (Fig 2 from Erbe et al. 2014). Creative Commons (CC BY 4.0).

Erbe et al. (2014) then were able to estimate the amount of audible acoustic energy (energy above the audiogram at each frequency) for different marine mammal species present in the Canadian Pacific region. Figure 2.13 shows that low-frequency baleen whales experienced much more acoustic energy from shipping in this area than species with poor low-frequency hearing.

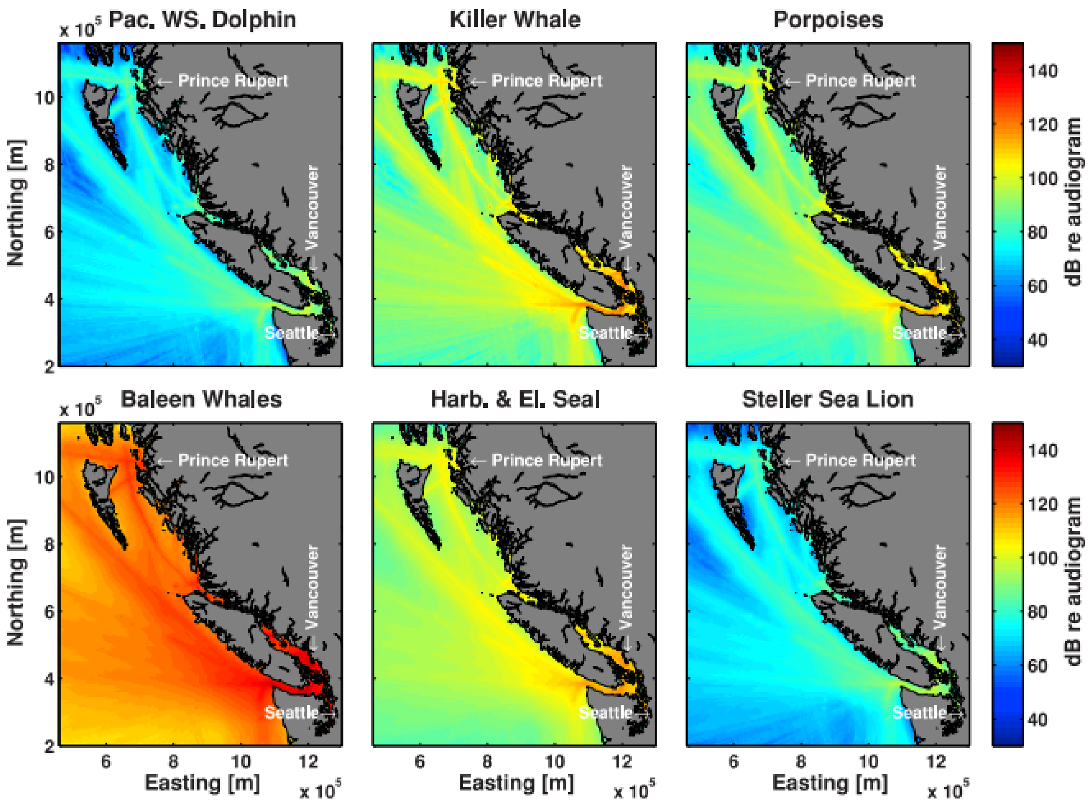



Figure 2.13. Estimates of audible acoustic energy from shipping as measured during the summer of 2008 by marine mammal taxa resident in the waters of British Columbia (Figure 4 from Erbe et al. 2014). Estimates derived from comparing the estimated spectra of shipping noise in a 5 km x 5 km grid against the frequency-dependent hearing sensitivity shown in Figure 2.12. Creative Commons (CC BY 4.0).

Figure 2.14 from Erbe et al. (2014) shows that by combining the audible energy map (Fig 2.14A) with a map of density of a species (Fig 2.14B), one can map hot spots where the most animals are exposed to the most sound energy in frequencies that they can hear. However, Erbe et al. (2014) note that different species not only hear differently, but they also respond differently to different doses of sound energy, so while this figure maps auditory exposure, this does not directly predict levels of response. The color bar of Fig 2.14C is labelled Risk Index, but it is better thought of as intensity of exposure to audible shipping noise rather than intensity of response to the noise, which depends upon the function relating acoustic dosage to response in this species.

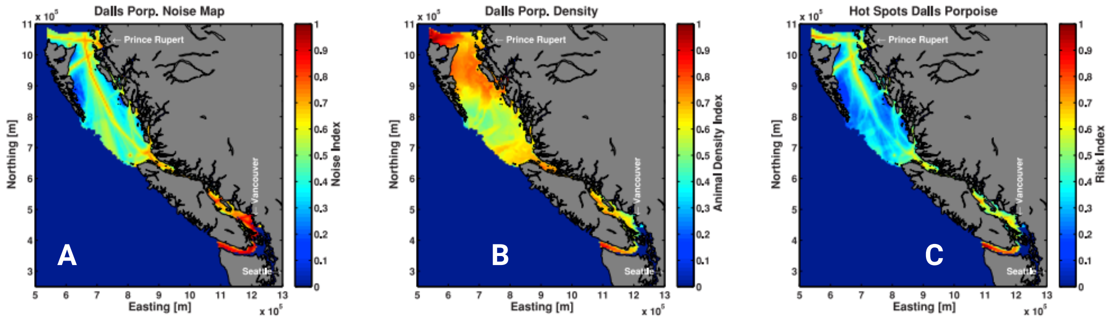



Figure 2.14. A: Audibility map of shipping noise for Dall's porpoise. B: Density map of Dall's porpoise. C: Product of audible sound energy times porpoise density to map hot spots of sound exposure for this species (Figure 5 of Erbe et al. 2014). Creative Commons (CC BY 4.0).

### 2.2.5.4 Acoustic measures of biodiversity and species abundance

The ability to separate sounds produced by marine life from natural abiotic and anthropogenic sound makes it possible to use acoustic recordings to estimate the diversity of biological components of ecosystems within range of the hydrophone. Ecoacoustic indices have primarily been developed for terrestrial habitats where they are used to quantify soundscape attributes including variability across time and/or frequency bands. For example, the acoustic complexity index (ACI), acoustic diversity index (ADI), acoustic evenness index (AEI) and acoustic entropy (H) have proven valuable for monitoring biodiversity and ecosystem complexity in terrestrial ecosystems (e.g., Dröge et al. 2021). Several of these indices have been tested recently in the marine environment. They do not seem to perform consistently across all marine investigations (Bohnenstiel et al. 2018, Minello et al. 2021), so further work needs to be done to validate their usage. However, promising methods exist for estimating the abundance of species that produce species-specific sounds. Many detectors exist that allow researchers to detect and classify calls from different marine species or species groups. Reliable detection of the calls of a species makes it possible to map the presence/absence of the species as long as some individuals call frequently enough for the space/time resolution of the survey (e.g., Picciulin et al. 2013). Once the number of calls per individual per unit time has been determined, then methods exist using sound propagation modelling to estimate the number of individuals of the species in the area sampled (Marques et al. 2013).

### 2.2.5.5 Studies on effects of human sound on wildlife

In some situations, monitoring the sounds produced by wildlife before, during, and after exposure to anthropogenic sounds makes it possible to study the responses of wildlife to particular sounds. For example, Moretti et al. (2014) studied the changes in echolocation clicks produced by Blainville's beaked whales, *Mesoplodon densirostris*, during foraging dives across periods prior to, during, and after naval exercises where mid-frequency active sonar was used in the vicinity of the whales. These observations make it possible to estimate the probability of whales initiating a foraging dive as a function of received sound pressure levels of sonar sound (Fig 2.15).

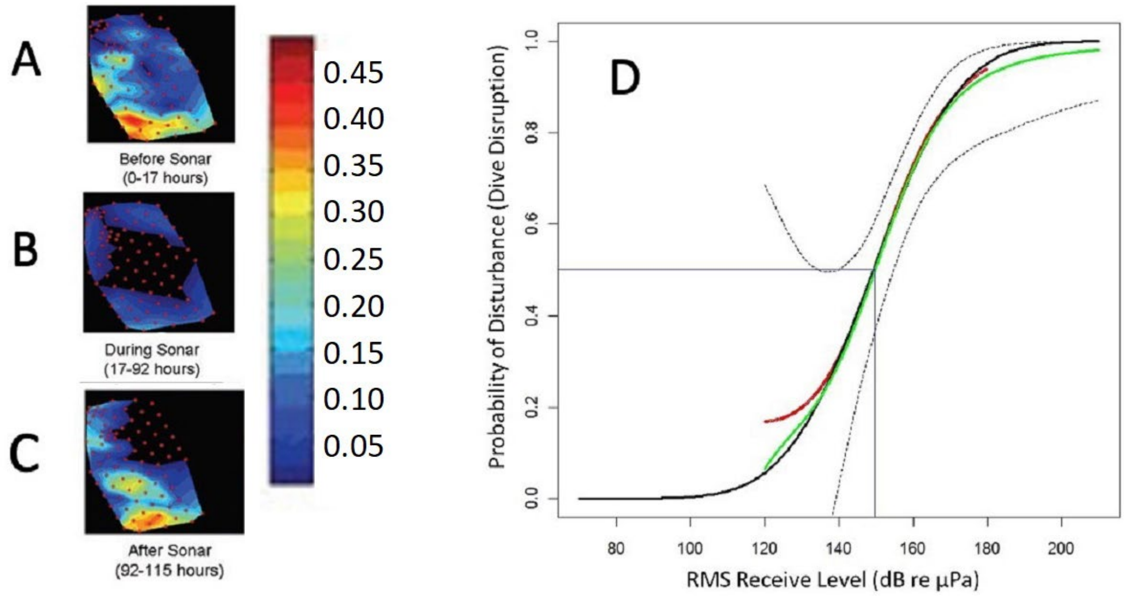



Figure 2.15 A-C: Maps showing the average number of foraging dives detected per hour by listening for echolocation clicks of Blainville's beaked whale, *Mesoplodon densirostris*, before, during and after naval sonar exercises in the Tongue of the Ocean, Bahamas (McCarthy et al. 2011). The color bar indicates the number of dives detected per hour on the hydrophones indicated as red dots. D: The probability that foraging dives are disrupted as a function of the maximum received level of sonar within half-hour intervals (Moretti et al. 2014). The solid black, red and green lines mark various model estimates of the dose-response function and the black dashed lines indicate 95% confidence intervals. The horizontal and vertical solid black lines show that a 50% probability of dive disruption occurs at a received level of 150 dB re 1 µPa. Permission for re-use granted by John Wiley & Sons.

### 2.2.6 Detecting transient events to monitor threats

If information about the precise signals produced by different sound sources can be used to detect and classify transient sounds to the source that made it, this information can be used to monitor the distribution of biotic sources such as soniferous species (part of the Ocean Health goals), natural abiotic sound sources such as earthquakes or tsunamis that are threats to humans and vessels, and human-made sound sources such as airguns and sonar that are threats to wildlife (part of the Monitoring Threats goals). The Ocean Sound EOV can facilitate the integration of data from a growing network of ocean sound observing systems into threat warning systems, especially in areas with limited funding where multi-purpose observing systems may be more cost-effective than separate sensor networks for each application. Areas such as marine protected areas and marine sanctuaries can be difficult to protect without continuous observations of some kind. In addition to providing a better understanding of the use of protected areas by soniferous organisms, passive acoustics can measure the levels of sound from commercial and recreational boats that enter protected areas, including illegal activity. For example, the SanctSound program monitors underwater sound in many of the U.S. National Marine Sanctuaries (https://sanctuaries.noaa.gov/news/feb21/sanctsound-overview.html). These applications of monitoring must acknowledge that significant harm can come from stressors such as anthropogenic sounds that originate far outside the borders that are controlled by protected areas. Passive acoustic monitoring can measure the level of sounds that originate from distant activities, such as shipping and seismic surveys, that may be far from these areas but impacting within them (e.g., Nieukirk et al 2012, Ryan et al. 2021).

## 2.3 Capacity building and technology transfer

Technological advances over the past few decades have enabled cost-effective measurements of ocean sound to be collected by civilian researchers with appropriate training. For example, Lamont et al. (2022) describe the HydroMoth, an underwater acoustic recorder that costs on the order of $100. The availability of inexpensive ocean acoustic equipment creates opportunities for training students, citizen scientists, technicians, and researchers to use this equipment and to analyze the data. Significant capacity development and technology transfer will be required to expand observations of ocean sound and to make acoustic data freely available globally, particularly in some coastal areas where the only ocean sound observations being collected are by the military and in regions that lack sufficient scientific infrastructure to purchase and maintain underwater acoustic recording systems. The Ocean Sound EOV should help reduce obstacles to timely open access to ocean acoustic data (to engage the public and streamline research and management use of ocean acoustic data) and should provide the impetus for the scientific community to facilitate technology transfer by (1) gathering evidence for the global demand for ocean observations; (2) fostering the development of low-cost underwater acoustic recording systems; (3) training network contributors in deploying equipment to obtain calibrated data; (4) defining standardized analysis output metrics suitable for a wide variety of comparative investigations; and (5) contributing standardized data to publicly available repositories.

# 3 MODES OF DEPLOYING ACOUSTIC SENSORS FOR OCEAN OBSERVATION

This chapter describes some modes for deploying technologies that can collect observations of ocean sound. As described in the previous chapters, the primary assets needed for acoustic observations are hydrophones and particle motion detectors. Hydrophones can be deployed from a variety of platforms, with differing costs and capabilities. Fixed hydrophones can be cabled to shore or autonomous, and hydrophones can be deployed on a variety of mobile platforms, including floating or subsurface buoys, autonomous underwater vehicles, towed from ships, or attached to animals. Each of the several kinds of particle motion sensors requires more specialized suspension and buoyancy adjustment systems than hydrophones do (Nedelec et al. 2016, 2021). For longer-term (months to years) observations of ocean sounds, hydrophones are usually either moored in the water column or on the seafloor. As mentioned in previous sections, different hydrophones and recording systems measure different sound frequency bands over different ranges of intensity, depending on the purpose of the measurements and the capabilities of the instruments.

## 3.1 Stationary platforms for deploying hydrophones

### 3.1.1 Cabled hydrophones

Cabled hydrophones are supplied by on-land power, can receive and transmit data in real-time and have been deployed in many locations. These include the triplets of hydrophones deployed by the CTBTO to monitor nuclear testing, and hydrophones deployed for research and management purposes by the Ocean Observatories Initiative,[1] Ocean Networks Canada, the ALOHA Cabled Observatory, and others (see https://iqoe.org/systems). Cabled hydrophones allow for rapid transmission and interpretation of data, unlike autonomous hydrophones, which are generally infrequently accessed. Real-time access to data is particularly important for applications where detection of a signal triggers notification of an immediate threat such as a tsunami or an observational opportunity where one might want to send vehicles to find the sound source and/or change acoustic sampling rates. Data available in real-time from cabled hydrophones made it possible to observe reduction in anthropogenic sound to the ocean associated with reductions in human activities associated with the COVID-19 pandemic in the Vancouver, Canada area much more quickly than would have been possible with the use of most autonomous hydrophone systems (Thomson and Barclay 2020). Cabled observatories can also deploy additional non-acoustic sensors that can help interpret acoustic observations, because power supply and data transfer rates are less limited than for autonomous instruments. Most cabled instruments are

1 https://oceanobservatories.org/

limited to deployment near land, although the land can be a mid-ocean island such as in the cases of the CTBTO hydrophones and the ALOHA Cabled Observatory. Underwater cables can be damaged by industrial activities such as trawling for fish.

“Smart cables” provide a potential new platform for cabled hydrophones. These cables are undersea fiber optic cables that cross ocean basins and offer the possibility for addition of hubs containing oceanographic sensors, including hydrophones (Howe et al. 2019b). For example, the Portuguese government is supporting a smart cable system connecting mainland Portugal with the Azores and Madeira with dozens of sensors placed over thousands of km (Howe et al. 2022). Even more novel is the concept of using fiber optic cables themselves as a sensor for ocean sound (Zhan 2019). Changes in temperature, strain, or vibration cause changes how light propagates through optic fibers. Distributed acoustic sensing (DAS) systems use a laser on an optic fiber to measure backscattered laser light. Timing the round trip allows one to measure changes on scales of several meters, providing the equivalent of very dense array of sensors. Such installations could provide acoustic measurements in the deep ocean and in areas within about 200 kilometers from shore where it is otherwise difficult or too expensive to deploy cabled hydrophones.

### 3.1.2 Fixed autonomous acoustic recording systems

Fixed autonomous acoustic recording systems are anchored in the water column or on the seafloor and acquire and store acoustic data internally; the recordings must be retrieved to access the data (Sousa-Lima et al. 2013). They can be mounted on or integrated into a variety of platforms, from moorings in the water column or on the seafloor, to opportunistic infrastructure such as oil rigs or offshore wind turbines. If the platforms to which hydrophones are attached generate sound, it may be necessary to minimize noise from the deployment platform and use filtering techniques during signal processing to reduce this noise. Of all forms of fixed hydrophones, autonomous instruments are the most widely used (see Figure 3.1). The main drawbacks of fixed autonomous recording systems are that most systems must be recovered to obtain the data they collect, and their deployment time is limited by data storage and battery capacity. The cost of ship time for deploying and recovering autonomous recording systems also can limit the use of these instruments. The need for recovery was a major limiting factor of this type of platform during the peak of the COVID-19 pandemic, when it was difficult to arrange for ships to service hydrophones and retrieve data, due to the restriction of human movement. Some of these instruments can telemeter acoustic and other data (Sousa-Lima et al. 2013), gaining some of the advantages of cabled systems, but the telemetry bandwidth is usually lower than cabled systems. Fixed autonomous hydrophones can be damaged by industrial activities such as trawling for fish, but the odds of damage to a hydrophone station is probably lower than that of damage to a cabled system that extends all the way to shore. Given this risk and the cost of cabled systems, there are likely situations such as sites far from land stations where autonomous platforms will be more cost effective than cabled systems, even adding in the cost of regular recovery and redeployment.

A fundamental resource for acoustical measurements is the global set of non-military hydrophones deployed worldwide. The IQOE maintains a database of the distribution of non-military moored hydrophones worldwide that have reported to IQOE that they are measuring and recording ambient sound. Figures 3.1a and b show the location of all hydrophone deployments from 1 August 1999 to 13 March 2023 (3.1a) and the subset of these hydrophones deployed for one year or more (3.1b).[2] The hydrophones in Figure 3.1 include moored hydrophones, cabled and autonomous, of at least 20 different models. The utility of a network moored hydrophones for ocean observations will depend on the long-term deployment of a minimum number of hydrophones sited in strategic locations. Deployment of a variety of different acoustic recording systems is not an issue, as long as they are properly calibrated and their data are processed in a comparable way following established standards. Short-term deployments can provide useful data for ocean observations. A large number of these hydrophones were sonobuoys deployed by the U. S. National Marine Fisheries Service and Australian Antarctic Division for short-term assessments and studies of fish and marine mammals. However, large gaps are obvious in the reports of deployments shown in Figure 3.1. We encourage operators of ocean acoustic recording systems to report relevant deployments, and this number may climb as more metadata are added.

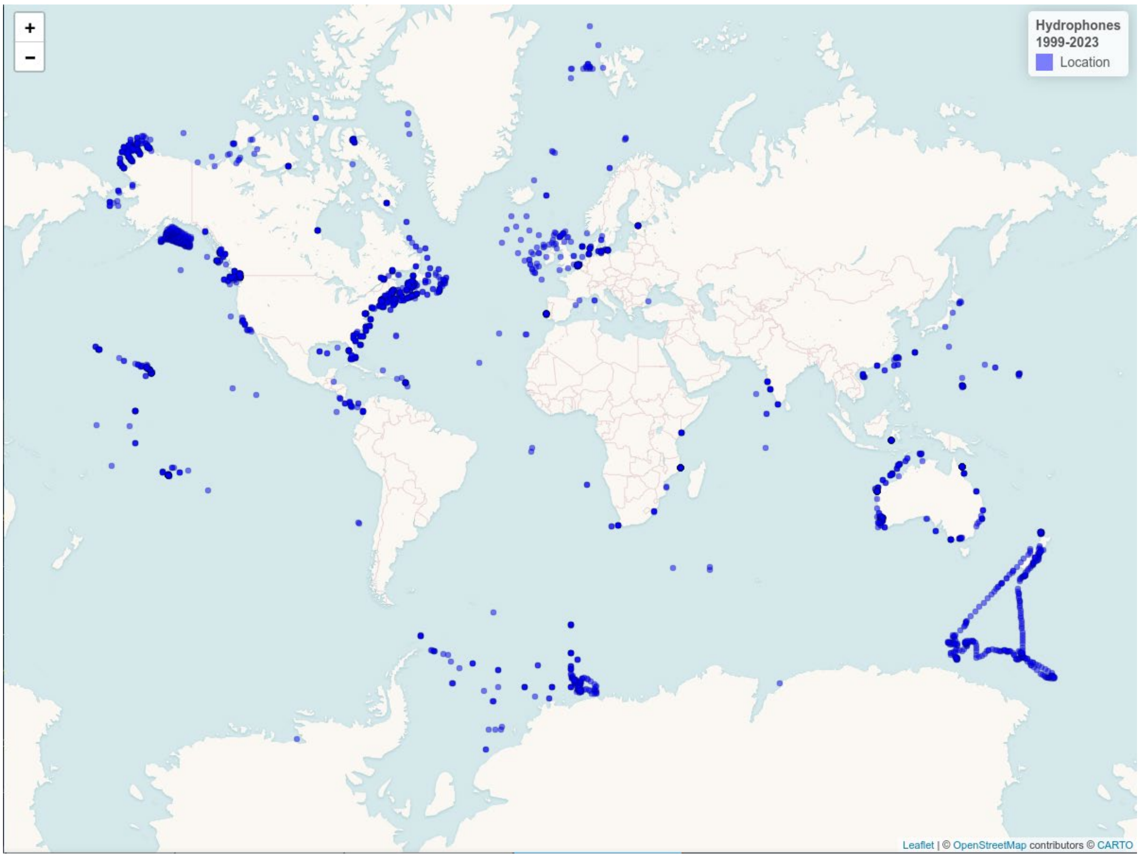



Figure 3.1a. Locations of non-military moored hydrophones worldwide that have reported to IQOE that were measuring and recording ambient sound from 1999 to 13 March 2023. Map created by Eduardo Klein.

2 We encourage any readers who deploy hydrophones to report hydrophone deployments to ed.urban@scor-int.org.

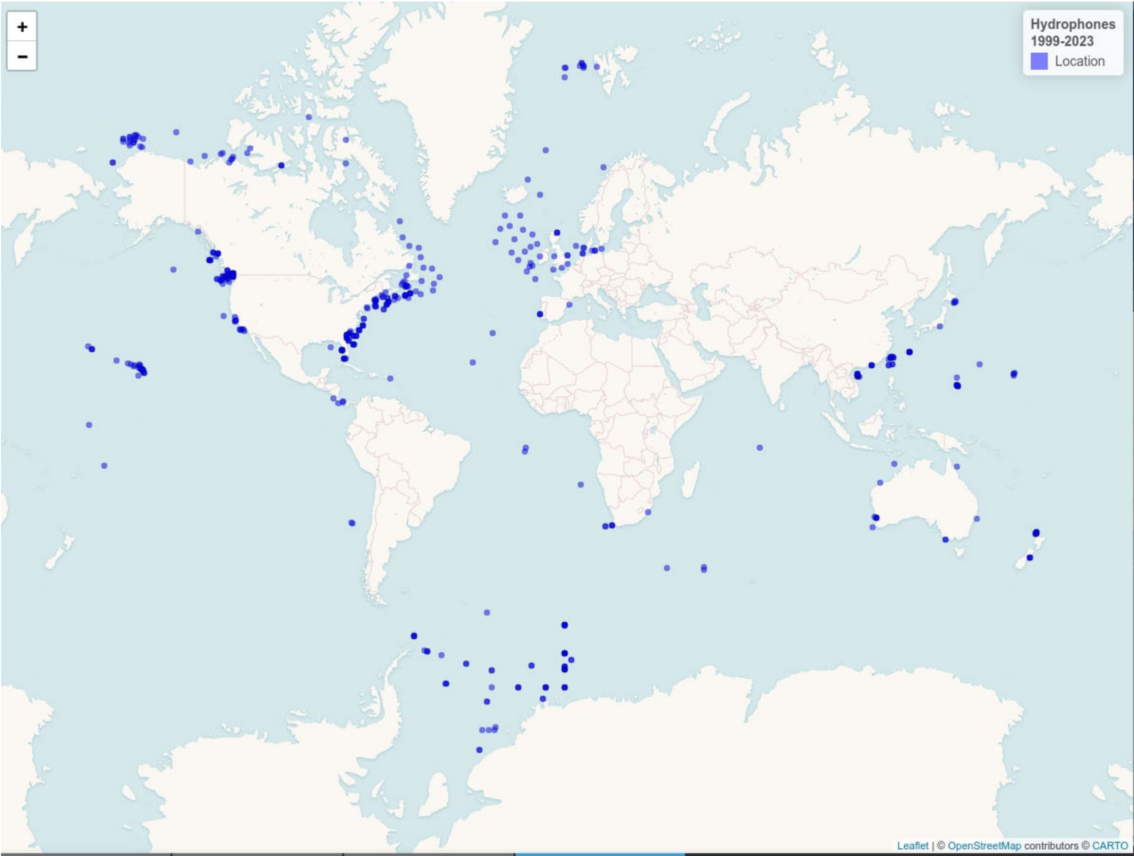



Figure 3.1b. Distribution of non-military hydrophone deployment sites worldwide that have reported to IQOE that were measuring and recording ambient sound continuously for one year or more. Map created by Eduardo Klein.

In addition to hydrophones, a global network of ocean bottom seismometers (OBSs) has been established that incorporates sensors to measure acceleration of the seafloor to detect earthquakes. Most OBSs are deployed by seismologists for research purposes. These instruments are primarily designed to detect earthquakes and ocean surface gravity waves but are equipped with hydrophones that collect data continuously at frequencies mostly below 100 Hz to record ocean acoustic signals generated by earthquakes. Their ability to record low-frequency sounds has been used to detect animals such as baleen whales that produce low-frequency sounds (Soule and Wilcock 2013, Matias and Harris 2015; Dreo et al. 2019) and they also have the potential to monitor ambient noise across these frequencies. Hundreds of OBSs have been deployed worldwide each year for research purposes (Figure 3-2). Coordinating sensors for multiple purposes on OBS platforms may reduce costs associated with the collection of observations and add to global assets able to monitor ambient ocean sound, including that produced by wildlife.

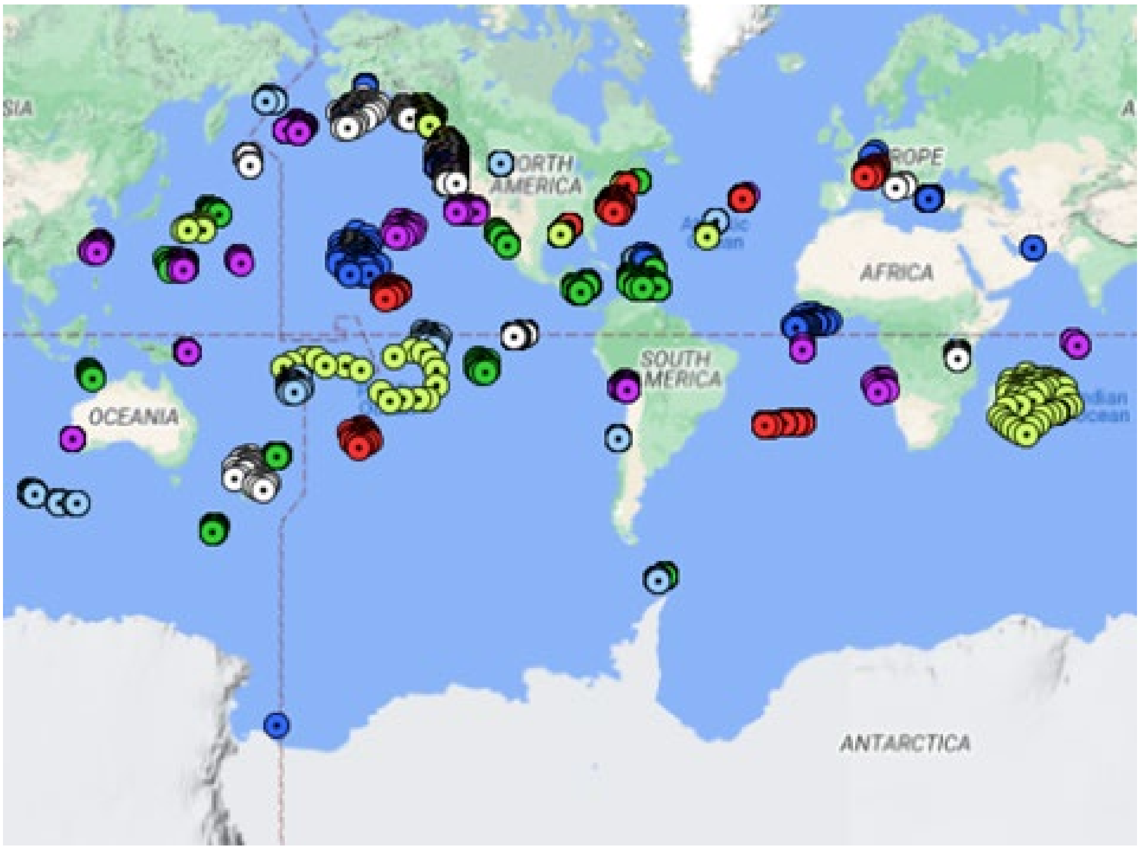



Figure 3.2. Ocean bottom seismometer (equipped with hydrophones) deployment locations reported to IRIS since 2000 (n = 2,768); accessed 5 May 2023. From Incorporated Research Institutions for Seismology Metadata Mapper. The number of OBSs deployed in any given year depend on research projects funded. Some nations do not supply their OBS metadata to IRIS. There appears to be fewer than 2,052 dots because at this map scale, many dots are shown in the same location. Station metadata in this map were requested from the EarthScope Consortium Web Services (https://service.iris.edu/). EarthScope Consortium services are funded through the Seismological Facility for the Advancement of Geoscience (SAGE) Award of the National Science Foundation under Cooperative Support Agreement EAR-1851048.

The current number of hydrophones deployed on OBSs worldwide is unknown, but there are at least hundreds. The majority of U.S. instruments are deployed by a national facility based at the Woods Hole Oceanographic Institution, the Scripps Institution of Oceanography, and the Lamont-Doherty Earth Observatory. U.S. institutions funded by NSF are required to submit their data to an open-access database. Germany maintains a pool of 70 OBSs through its DEPAS[3] ("Deutscher Geräte-Pool für amphibische Seismologie" / "German instrument pool for amphibious seismology"). Some of these OBS data are listed on the PANGAEA repository: https://www.pangaea.de/?q=ocean+bottom+seismometer. Other countries—notably Canada, France, the United Kingdom, and Japan—also deploy OBSs. Some data from these countries may be available.

3 https://www.awi.de/en/science/geosciences/geophysics/methods-and-tools/ocean-bottom-seismometer/depas.html

## 3.2 Mobile platforms

### 3.2.1 Human-occupied vessels

Human-occupied vessels are the classic mode for mobile deployment of hydrophones. For more than a century, ocean acousticians have mounted hydrophones on the hull of ships or towed them behind ships to record underwater sound. Most of these recordings are made for specific research purposes, and few central archives curate open-access vessel-based recordings. Ships can record sound from fixed stations, along survey lines, or following targets of opportunity. Apart from difficulties deploying deep hydrophones from a surface vessel, vessel deployment remains one of the most flexible modes of deployment. However, the cost of ship time limits the coverage available for ship-based acoustic observing systems.

A variety of mobile platforms deployed more recently have been adapted to host hydrophones, including drifting floats, gliders, submersibles, and animal-borne platforms.

### 3.2.2 Drifting floats

Drifting floats are platforms that can change their depth by adjusting buoyancy, but that otherwise travel passively along with ocean currents. They may adjust their direction of travel by stopping and "parking" at different depths, where currents run in different directions. Argo floats are an example of these platforms. These instruments use deep-ocean currents to travel horizontally at pre-selected density surfaces (roughly correlated with depth), while periodically taking profiles of ocean variables vertically from as deep as 2,000 m to the surface. Observations from a fleet of more than 4,000 floats have revolutionized our understanding of ocean currents, water mass structure, and heat content of the upper 2,000 m of the ocean because of the large number of multivariate profiles that can be collected more cost-effectively from geographically dispersed locations than from ships (Wong et al. 2020). The global status of the Argo float program can be found at https://argo.ucsd.edu/about/status/.

Several Argo floats have recently been equipped with additional sensors for chemical, biological, and other parameters and/or been adapted for deployment down to 6,000 m depth. A small number of Argo floats have included hydrophones, with the primary purpose of observing changes in wind and rainfall (Yang et al. 2015; Riser et al. 2019) by sampling sound in the frequency range of 300-40,000 Hz. The acoustic data telemetered from these float-based hydrophones is limited by the bandwidth for transmitting data over the Iridium satellite network and, as a consequence, they do not monitor continuously, and so are less useful for ensuring detection of brief rare events. It is unlikely that hydrophones will be widely deployed on Argo floats in the near future, because of the competition for space and power available on the floats. However, data from these floats could make important contributions to time series of ambient noise in the ocean. The Ocean Sound EOV can help to advocate for acoustic sensors on these platforms.

Another autonomous drifting platform for hydrophones is Mermaid floats,[4] which like OBSs, are primarily designed to detect earthquakes, but are also useful for more general ocean acoustic monitoring (Pipatprathanporn and Simons 2021). Fifty-four Mermaid floats were active in January

4 http://geoweb.princeton.edu/people/simons/earthscopeoceans/

2023. The floats collect acoustic and seismic data related to earthquakes while parked at a depth of 1,500 m. When an earthquake is detected above a pre-set strength, the float rises to the ocean surface and reports data filtered for seismic signals and sounds below 20 Hz via an Iridium satellite link. These floats store one year's worth of raw acoustic data but are not intended to be recovered; only processed data are relayed by Iridium. However, the floats can be recovered at the end of the year to retrieve the data and recovery can be economical if the float is near land. There was recently a 7-float experiment in the Mediterranean Sea that intended to capture acoustic data and recover the floats for data download. Acoustic signals could be processed onboard the floats to relay spectral probability densities of acoustic signals for any desired time period from hours or longer and they could be adapted to sample across all depths at which they are capable of being deployed. In present deployments, the floats surface on average every 6.25 days, so transmission is relatively frequent and surfacing time can be pre-set, depending on the sampling design. Mermaid floats could be deployed to conduct missions for both seismic and ocean acoustic observations, with cost sharing by different users. All could be equipped with suitable hydrophones to observe and report ambient noise, supported through collaborations between the marine geophysics and ocean acoustics communities. The addition of acoustic systems designed to record ambient sound or non-earthquake signals on MERMAID floats will depend on ocean acousticians working with marine geophysicists to make requests to funding agencies to fine-tune the design of floats for these additional purposes.

### 3.2.3 Autonomous underwater vehicles

Autonomous underwater vehicles (AUVs) travel through the water untethered and propelled in the horizontal direction by either electric propulsion or, in the case of gliders, a combination of ocean currents, changes in buoyancy, and adjustable rudders. Power, sensing, and computing capabilities are self-contained. AUVs propelled by battery power typically have a shorter deployment period than gliders and typically generate more noise than gliders. AUV routes can be either pre-programmed or can be modified *en route* according to pre-determined decision rules (e.g., Zhou et al. 2018). Gliders are capable of missions across ocean basins (Testor et al. 2019). Hydrophones have been deployed on gliders by many research groups globally. Some gliders have low enough flow noise that acoustic recordings can be made while the gliders are moving, although others must stop to gather data on ocean soundscapes, including ambient sound and sounds from animals. Gliders have been used to estimate wind speed acoustically (Cauchy et al. 2018) and several groups are using them to track whales (e.g., Küsel et al. 2015; Cauchy et al. 2020; Mellinger et al. 2021). An international coordinating body has been formed (https://www.oceangliders.org/) and the positions of glider deployments are shown on their website.

### 3.2.4 Autonomous surface vehicles

Autonomous surface vehicles (ASVs) are platforms that float or sail on the ocean surface and are powered by electric propulsion or moved by wind and ocean currents. ASVs have been used to map the sounds made by cetaceans in the south Atlantic Ocean (Bittencourt et al. 2018), to map fish spawning aggregations (Chérubin et al. 2020), and to detect baleen whale calls (Baumgartner et al. 2021). Surface platforms can be powered by solar panels and/or rigid sails that catch the wind and they have an advantage over submerged platforms in the ability to locate the acoustic observations more precisely in time and space because they have more continuous access to GPS satellites. ASVs can also telemeter data more frequently than AUVs which must surface to telemeter data. Some larger ASVs can be leased (e.g., SailDrones) for long deployments, although current costs for rental of ASVs is high enough to inhibit single use for the collection of acoustic observations. However, hydrophones deployed on shared missions with clients measuring other variables could make collection of sound observations using these technologies economically feasible. The placement of hydrophones in the ocean surface layer could provide data on surface processes that are not often available from other hydrophones.

### 3.2.5 Digital Acoustic Recording Tags

Digital Acoustic Recording Tags are small electronic tags that can be deployed on marine animals and include hydrophones to sense sound. Other sensors may be added, such as pressure sensors for depth, and 3-axis accelerometers and magnetometers to sense animal movement and orientation. These tags have been used to better understand the behavior and ecology of marine vertebrates (seals: Burgess et al.1998, sharks: Meyer et al. 2007) and changes in these that might be associated with responses to anthropogenic sound (Johnson and Tyack 2003, Johnson et al. 2009, Fregosi et al. 2016). These tags can record ambient sound, anthropogenic signals, animal vocalizations, and the orientation and movements of the animals to which they are attached. The main drawbacks of these tags in terms of widescale deployment for the collection of sound observations are that they are labor-intensive to affix to animals and they must be retrieved from the animal in order to download the data collected. As animals move and break the surface to breathe, the sound of water flowing past the hydrophone generates noise that interferes with the ability to measure distant sound sources. Most digital acoustic recording tags also have limited deployment lengths; they remain attached to animals for a maximum of only a few days and in many cases, only a few hours. However, for many species, they provide important high-quality recordings of sounds that can be attributed to the tagged animal (important sound source data, Parsons et al. 2022) and provide information on individual calling rates (critical data for models that estimate animal numbers from detection of calls, Marques et al. 2013), while also providing information on how sound production varies with behavioral state. In relation to the Ocean Sound EOV, acoustic tag data are particularly important to understand how individual animals react to acute exposures to ocean sound, especially sound from anthropogenic sources. The requirements for these tags to be small, rugged, and low power may make them useful for adapting to some GOOS platforms.

## 3.3 Planning for cost-effective long-term ocean acoustic observations

We have enough experience with these modes of observation to estimate costs over the lifetime of long-term monitoring systems. Sharing acoustic sensors and recorders with data transmission cables and platforms that deploy other sensors links all of the data streams to one location and will usually reduce costs for all users.

# 4 TAILORING ACOUSTIC OBSERVING SYSTEMS FOR DIFFERENT USES

The different modes of deploying hydrophones discussed in Chapter 3 are suited for making recordings over different scales of time and space. Figure 4.1 sketches how the ocean sound applications for each of the three primary GOOS focus areas (shown on the right side of Figure 2.1 and the left side of Figure 4.1) cover different spatial and temporal scales. Figure 4.1B illustrates different space-time coverage required for the three GOOS primary goals, with color coding corresponding to those in Figure 4.1A. Figure 4.1C shows the coverage provided by each mode of deploying sensors for the Ocean Sound EOV. Figure 4.1B shows that observations designed to measure climate change must operate from areas with spatial extents of about 1 km over timescales of about a month to cover local seasonal changes up to the global spatial scale over durations of a century or more. Fixed recording stations are likely to be the most appropriate for the longer time-space scales, as exemplified by the CTBTO global observing system. Monitoring of threats usually requires real-time reporting on time scales of minutes to hours and spatial scales of 1 km to global. Acoustic monitoring of ocean health requires intermediate scales of days to decades and 100 m to 100 km.

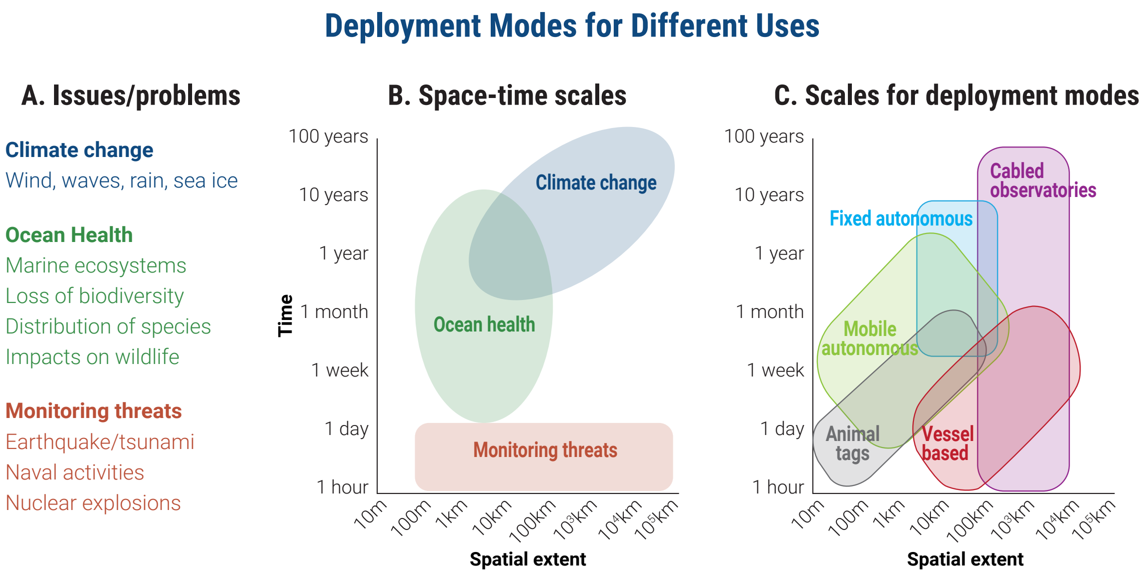



Figure 4.1. Overview of implementing the Ocean Sound EOV. Figure 4.1A color codes the main societal issues and problems for which the Ocean Sound EOV provides observations. Figure 4.1B uses the same color code to sketch the space-time scales required for observations relevant to each problem, and Figure 4.1C illustrates the coverage that several modes of deployment of ocean acoustic sensors can provide in terms of space on the x-axis and time on the y-axis.

Acoustic pressure and particle motion are the primary acoustic variables for ocean sound described in the Ocean Sound EOV specification sheet and illustrated in Figure 2.1. Some features of how sound propagates in the ocean help to define the spatial range of different sound frequencies. The range over which a sensor is likely to detect sounds is strongly influenced by the upper frequencies that need to be detected because the higher the frequency of sound, the more energy is absorbed by passage through seawater (Fisher and Simmons 1977). Absorption is insignificant for global sound paths at frequencies below about 100 Hz, which is why this low-frequency region is targeted by the global systems with few receivers (e.g., the CTBTO hydroacoustic ocean monitoring network). While low-frequency ship sounds and whale calls can be detected at hundreds to thousands of km, the echolocation clicks of Blainville's beaked whales, which have a center frequency of about 40 kHz (Johnson et al. 2006), seldom can be detected at ranges > 6 km (Marques et al. 2009). The spacing between hydrophones in the array illustrated in Figure 2.12A-C is about 4 km, which makes it well suited for detecting beaked whale clicks over an area of ~1500 km$^2$ (McCarthy et al. 2011). If monitoring for transient sounds such as beaked whale clicks is used to make operational decisions, then real-time availability of the data is often important, which suggests the use of cabled arrays for fixed areas, and for mobile platforms such as vessels where humans can make decisions, or autonomous platforms that can telemeter data with only short delays. These constraints are less relevant for observation applications that do not require real-time feedback. The limited range for detecting higher frequency sounds means that mobile platforms are often required for high-frequency sounds to be observed over the coverage areas required for different applications, not to mention the global coverage aim of GOOS. Some surveys using ocean sound may require vessels that can maintain a pre-planned track, but many other applications can take advantage of platforms that cannot fully compensate for currents and take advantage of their lower cost for increased numbers and spatial coverage.

Chapter 2 listed a series of ways that observations of ocean sound can be used to inform societal needs. Chapter 2 starts by discussing applications that can be addressed by the primary ocean sound variables alone, and then discusses other ocean sound applications that require supporting variables and environmental parameters. Chapter 3 introduced the different modes for deploying acoustic sensors. Here we integrate all of this information to discuss how to design acoustic observation systems for different applications. Table 4-1 lists a set of these applications, describing their products, modes of deployments of acoustic sensors, and other data needed in addition to ocean sound.

Table 4-1 Design of acoustic observing systems for different uses and products. The uses of observations were described in Chapter 2, with examples of most of the products listed below. Products would be mainly for use of decisionmakers, policymakers, and for public education.

| Use of Observations | Product(s) | Modes of Deploying Acoustic Sensors | Other data needed (GOOS EOVs indicated in red) |
|---|---|---|---|
| Estimating long-term changes in levels of ocean sound | Time-series plots of sound pressure levels at different frequencies in regions of the global ocean<br><br>Could include historic data, as available. E.g., Fig. 2.3 | Cabled or fixed autonomous sensors moored to seafloor, ideally from multiple carefully selected sites over long time periods | None |
| Sound levels to monitor trends at sentinel locations | Statistics of sound pressure levels over specified frequency bands of samples of specified durations (e.g., Fig. 2.2); or outputs of MANTA (e.g., Fig. 2.4) | Cabled or fixed autonomous sensors moored to seafloor | None |
| Acoustic observations as a tool to monitor abiotic sources: ocean wind, sea state, rain, ice cracking | Figures of trends of these measurements globally and/or at sentinel sites. E.g., Fig. 2.9 | Moored or mobile sensors that can estimate sound energy over the frequency ranges and the geographical locations of interest | Acoustic characteristics of each sound source<br><br>Useful to compare with data from the following EOVs: Sea ice, Sea surface height, Sea state |
| Acoustic observations as a tool to monitor transient abiotic events such as earthquakes, volcanic eruptions | Real-time alerts on detection and classification of these events. Tabulation of time, location, and strength of events | Moored or mobile sensors that can estimate sound energy over the frequency ranges and the geographical locations of interest | Acoustic characteristics of each sound source |

| Use of Observations | Product(s) | Modes of Deploying Acoustic Sensors | Other data needed (GOOS EOVs indicated in red) |
|---|---|---|---|
| Detection of sound-producing organisms to estimate their abundance, distributions, and migrations | Maps of acoustic detections of specific marine mammal, fish and invertebrate species (e.g., Fig 2.15A-C)<br><br>Change in species abundance and distribution over time. Acoustic biodiversity indices | Enough sensors to sample the species/ sounds of interest in the study area<br><br>Mobile sensors often best for signals with limited range of detection vs area to be surveyed<br><br>Moored sensors often better to study temporal trends | Acoustic characteristics of calls<br><br>Calling rates of individuals required to estimate abundance<br><br>Useful to compare with data from the following EOVs: Marine mammal, fish and invertebrate abundance and distribution |
| Mapping sound fields, assigning sound fields due to each source type, estimating sound budgets, and predicting soundscape changes | Tables of sound sources indicating the amount of energy or percentage of total energy estimated from each source type over specified frequency bands and time periods (e.g., Table 2.1) | Local measurements for validation of modelled sound fields can be made by moored or mobile sensors that can measure sound energy over the frequency ranges and the geographical areas of interest | Acoustic information on different sound sources and how these move in the study area<br><br>Variables required to model sound propagation such as temperature and salinity in the water column and sea surface and seafloor information |
| Impacts of anthropogenic sound on distribution and behavior of sound-producing animals | Changes in calling rates and/or distributions as a function of exposure (e.g., Fig. 2.15) | Enough sensors to sample study area<br><br>Synchronized sensors useful for localizing sound sources | Acoustic characteristics of calls<br><br>Variables that affect sound propagation |

## 4.1 Long-term changes in ocean sound levels

Changes in sound levels in the ocean over time have not been widely documented in the peer-reviewed literature. Time series of ambient sound in the ocean have not been sampled regularly enough at multiple locations to indicate how sound is changing in the ocean globally. This data gap makes it difficult to assess whether and where sound pollution is increasing, which changes in sources contribute to sound pollution, and how and where to design mitigation efforts if there is a problem. A useful product from the Ocean Sound EOV would be time series of ocean sound from a carefully selected set of specific locations (see also next section), updated on an annual basis that would support analyses of changes at different frequencies over time. This will require regular sampling of sound analyzed in a standardized manner (see Chapter 5 and the recommendations in Appendix II) at intervals short enough to allow for analysis of diurnal, seasonal, and annual changes. For efforts to quantify long-term trends in ocean sound, the need to account for strong seasonal changes is illustrated in Figure 2.3 from Harris et al. (2019). Merchant et al. (2016) used ambient ocean sound recordings from sites off the United Kingdom to argue that it would require decades of monitoring to develop the statistical power to detect long-term changes of 1-3 dB per decade. The requirements for long-term frequent, if not continuous, sampling from specific sites argues for fixed hydrophones. When feasible, cabled sites are likely to provide the most reliable long time series, especially if these systems can rapidly be repaired if faults are detected. For sites where cabling is unrealistic, autonomous moored hydrophones can sample and record the data required (e.g., Warren et al. 2018), but the need for expensive regular servicing of the moorings raises concerns about reliability and continuity of long-term data, especially in difficult-to-reach remote areas.

## 4.2 Sentinel locations to monitor trends in ocean sound

A set of "sentinel" locations could be selected to determine levels of ocean sound and how much ocean sound is changing. Different criteria can be used to select sentinel locations. One important criterion is selecting locations and depths that are well suited for covering the study area with as few sensors as possible. For example, the CTBTO selected 11 sites that could detect underwater nuclear explosions in any ocean. Given the Northern Hemisphere bias in the network of passive acoustic monitoring locations worldwide, as indicated in Figure 3.1, another criterion might be to select locations with poor coverage, such as most of the Southern Ocean. Another criterion for selecting sentinel locations might be to study sites that are currently quiet or noisy, perhaps with changes in sound production or propagation planned or expected. Changes in ocean sound may be expected due to changes in human sound-producing activities or due to climate change-driven shifts in ecosystems. The SanctSound project selected sentinel locations in U.S. marine sanctuaries to monitor their soundscapes. The sentinel location concept calls for fixed hydrophone sites, but the decision about cabled or autonomous may depend upon logistics and the duration of time series anticipated for the application. Selection of sentinel sites will often depend upon local priorities but could be supplemented through an open workshop involving the international ocean acoustics and bioacoustics communities.

## 4.3 Acoustic observations as a tool to monitor abiotic sources: Ocean wind, sea state, rain, sea ice, earthquakes, volcanic eruptions

Methods to detect the intense acoustic signals from earthquakes and volcanic eruptions are well developed. The most intense signals can be detected in real time from cabled moored systems such as the CTBTO hydroacoustic hydrophone network, while autonomous drifting platforms such as the MERMAID floats can detect signals and telemeter detection information after short delays. Near real-time feedback is critical for systems that monitor threats such as tsunamis that may require rapid reactions. Methods for quantifying ocean wind, sea state and rain have been demonstrated (e.g., Pensieri et al. 2015) but are not widely employed. Methods for quantifying the contributions of ice to the soundscape, both in terms of making sound when it cracks (e.g., Dziak et al. 2015) and reducing the sounds from breaking waves are in their early stages of development. Figure 2.9 shows how annual variations in ocean sound measured from cabled hydrophones may be related over long ranges to abiotic sources such as ice cover, wind and rain. Sensors on autonomous buoys have also been used to measure sound from rain, wind and breaking waves at closer ranges (Ma et al. 2005). An observing system that aims for global coverage will probably require a combination of moored and mobile sensors for appropriate spatial sampling. Addition of hydrophones to a global set of platforms such as the Argo floats could help meet this aim. This application requires information about the acoustic characteristics of each abiotic source of sound and would benefit from information about these sources such as provided by the EOVs on sea ice and sea state.

## 4.4 Detection of sound-producing organisms to estimate their abundance, distributions, and migrations

Methods to detect sound-producing organisms by their calls require the ability to classify calls to the taxonomic level of interest, usually to the species level. Studies that classify biotic sounds by taxon of marine life are well established. For marine mammals, this is a mature field with regular international workshops held every 2-3 years since 2003 on detection, classification, localization and density estimation of transients where test data sets are analyzed by multiple independent groups (e.g., https://www.cetus.ucsd.edu/dclde/). Looby et al. (2022) published a global inventory of soniferous fish diversity that estimates the percentage of soniferous species for major fish taxa. A recent paper by Parsons et al. (2022) advocates the development of an open-access international database of the biotic sources of ocean sound. Ocean sound observation systems that estimate the abundance, distribution, and migrations of sound-producing organisms should deploy enough sensors for adequate sampling of the study area over the planned duration. The resolution required depends upon the design of the specific study. This may be achieved with fewer moving sensors than fixed sensors, but fixed sensors can more easily measure temporal trends in the same site. Methods that localize calling animals by measuring delays in the time of arrival of signals require arrays of sensors whose recording systems are synchronized in time. Marques et al. (2013) review requirements for estimating abundance and distribution from call-rate data. Many approaches require knowledge of individual calling rates to convert the number of calls detected to the number of individuals.

## 4.5 Mapping sound fields, estimating the spectral composition in the sound field due to each type of sound source, estimating sound budgets, and predicting soundscape changes

Mapping the sound field of a specified area of interest requires modeling of sound propagation to estimate sound levels over the area. Measuring sound levels at a set of sites is important for verifying these estimates. Sound propagation models coupled with knowledge of locations and acoustic characteristics of relevant sound sources can produce maps of sound fields and can also help establish a strategy for spatial sampling of ocean sound, which can be used to define the locations and durations of acoustic observation that minimize uncertainty in the model results. Verifying maps of the sound field may not require sampling from specific locations for time periods as long as those required for monitoring long-term trends in ocean sound. Modes of deployment could include fixed and/or mobile sensors best suited to minimize uncertainty about the overall sound field. Validation of models and of the input data they use (propagation variables in Figure 1.2) and establishment of standards for which settings are appropriate for each will be important for reliability of these ocean sound observations. There are standard databases for variables used in sound propagation models, but model results are only as good as the input data. It is often useful to measure the supporting variables such as temperature and salinity in the water column at the times and areas being modeled.

Estimating sound budgets also requires the capability to assign sound fields to each sound source type. This requires both information about the acoustic characteristics of each source and the locations of activities using these sources in the study area. Many research efforts have characterized sources of ocean sound, but existing sound source information does not currently meet GOOS requirements in terms of standardization and open-access. Users of this information globally would benefit from standardized open-access databases of sound produced by known biotic and abiotic sources, including anthropogenic sources. Just as critical are data on where and when human sound-producing activities take place. Obviously, the humans conducting sound-producing activities know when and where they are operating, but these data are not freely accessible for many important sound sources. The AIS transponders carried by large ships provide data on location, speed, and other relevant data. However, small vessels can be significant contributors to coastal soundscapes, but are seldom tracked by AIS. Databases on operation of loud impulse sources such as seismic surveys are required by the European Union Marine Strategy Framework Directive (e.g., https://www.ices.dk/data/data-portals/Pages/impulsive-noise.aspx) and are also maintained by relevant industries (e.g., the International Association of Geophysical Contractors for seismic surveys). However, these data are not always open-access and may not provide enough information to predict sound fields.

Once soundscapes are better characterized, it may be possible to predict changes in sound in specific locations of interest due to natural seasonal processes and climate modes (e.g., the El Niño-Southern Oscillation), and changes in human activities such as shipping, seismic survey, marine construction, etc. (e.g., Figure 2.11). As discussed in Section 2.2.6, this capability would be very useful for proposers and regulators of marine activities to estimate the acoustic impact of new developments and also decide which sound-producing activities to reduce in order to mitigate adverse impacts of ocean sound on ecosystems.

## 4.6 Impacts of sound on the distribution and behavior of sound-producing animals

The ability described in Section 4.5 to map the sound field from a human activity and the ability described in Section 4.4 to detect the calls of sound-producing animals make it possible to study the impacts of human sound on the calling behavior and distribution of sound-producing animals. These methods have provided an important way to monitor the impacts of these activities on acoustically sensitive species. A common approach involves placing sensors at varying ranges from a sound source and comparing the rates of calls detected at increasing ranges from the source and decreasing sound levels received from the source (e.g., Figure 2.12, Moretti et al. 2014). The Ocean Sound EOV aims to provide a repository for measurements and models of sound levels and marine mammal distributions that could be analyzed to determine the changing effects of human activities on acoustically active marine life.

# 5 STANDARDS, BEST PRACTICE AND DATA MANAGEMENT FOR OCEAN ACOUSTIC OBSERVATIONS

GOOS and its Observations Coordination Group (OCG) have defined a set of attributes that mature observation networks must meet for EOVs in the global ocean (GOOS Report 266). Observations must be designed to be sustained over many years, beyond the lifespan of individual research projects or experiments. They should be designed for spatial scales that are larger than regional, with an intention for global coverage. Observation systems must develop and follow standards and best practices. Data and complete metadata must be provided on a FAIR-compliant basis (Findable, Accessible, Interoperable, and Reusable as described in Wilkinson et al. 2016) for real-time and delayed data delivery. Here we discuss standards, best practices, and data management issues for the Ocean Sound EOV.

## 5.1 Standards and best practices

To produce global datasets and products, measurements must be collected and/or processed in such a way that they are comparable over space and time, by whatever instruments or observation methods are used. To achieve comparability of acoustic measurements, it is important to identify and reduce variations in measurements that result from differences in sensors (for sound pressure and particle motion), how they are calibrated and used, and how data from these instruments are analyzed and archived. The Ocean Best Practices System (www.oceanbestpractices.org) includes a good practice guide for underwater noise measurement (Robinson et al. 2014). Warren et al. (2018) provide a detailed good practice guide for deployment of acoustic sensors towed from vessels and on bottom-lander systems, along with measurements of acoustic propagation in the vicinity of the autonomous recorders. The need for standardizing how particle motion is measured and reported has recently been recognized (Nedelec et al. 2016). This led to the development of a best practice guide (Nedelec et al. 2021) with guidelines to ensure that particle motion measurements are correct, meaningful, consistent, and comparable among studies. Researchers, consultants, and regulators who wish to measure or understand measurements of underwater particle motion are encouraged to refer to the Nedelec et al. (2021) best practice guide.

The basic foundation for comparable reporting is standardized and internationally agreed and quantitatively defined terms for measurements. The International Organization for Standardization (ISO) developed ISO Standard 18405:2017 on Underwater Acoustics – Terminology[5] to help ensure that reported measurement results are consistent across projects and is also developing ISO Standard 7605 on measurement of underwater sound[6]. The IQOE WGs on Standardization and Marine Bioacoustical Standardization convened a meeting in 2019 to develop IQOE guidelines for measuring, processing, and reporting of ocean sound levels.[7] This workshop built on work done by national and regional research projects and was intended to help make observations collected in different places comparable. The recommendations from this workshop in terms of acoustic measurements were adopted by the Ocean Sound EOV Implementation Committee.

Appendix II summarizes recommendations for processing acoustic data to characterize how ambient ocean sound varies in frequency and time, suitable for analysis of soundscapes and to study long-term trends in ocean sound. These guidelines were developed on the basis of experience and decisions made by national and regional projects regarding standard guidelines for processing and reporting soundscapes, such as the ADEON project in the United States and the JOMOPANS project in Europe. In addition to guidelines, standardized treatment of data requires open access software that follows the guidelines. For a recent example, the MANTA software was developed to process sound files according to the Guidelines for Observation of Ocean Sound and ISO standards (Miksis-Olds et al. 2021). MANTA software is available at https://bitbucket.org/CLO-BRP/manta-wiki/wiki/Home and could serve as a required processing step for noise statistics available through GOOS-related data repositories or portals. MANTA includes standards for measurements and associated metadata, statistics, and predictions.

Currently, researchers are actively developing methods using ocean acoustic data to estimate abiotic variables such as wind, rain, sea state, and state of sea ice. Research is equally active in estimating biotic variables by detecting sounds produced by vocal animals, categorizing them to taxon, and using information on calling rates and sound propagation to estimate their density and abundance. Over time, as these methods mature and are validated, standards and best practices for analyzing ocean acoustic data to estimate abiotic and biotic information will be critical for accepting them as a mature part of the Ocean Sound EOV.

5 https://www.iso.org/standard/62406.html

6 https://www.iso.org/standard/82844.html

7 See workshop report at https://scor-int.org/IQOE/IQOE_2019_Standards_Workshop_Report.pdf.

## 5.2 Data management for the Ocean Sound EOV

Data available from the GOOS network and partners should focus on measurements that feed into observations and predictions made on a routine and sustained basis, in addition to being available to contribute to answering research questions. The Ocean Sound EOV will require data from sound recording/measuring instruments to be accompanied by a set of required and standardized metadata, such as calibration data (e.g., on the sensitivity of the hydrophone as a function of frequency and directionality of the receiving system) and processed into SI units. Separate efforts will be required to establish and integrate sound source databases (e.g., Mellinger and Clark 2006, Parsons et al. 2022).

GOOS does not hold data, but most GOOS components have international data repositories or portals that are associated with GOOS. The usual repository for the biology and ecosystems EOVs is the Ocean Biodiversity Information System or OBIS (https://obis.org). However, Ocean Sound is a cross-disciplinary EOV, and ocean sound data are typically time series of physical variables such as sound pressure levels sampled at rates of hundreds of Hz to hundreds of kHz and spectra sampled every minute with much higher data rates than typical for the OBIS system. Rather than burdening OBIS with large volumes of new data types, the Ocean Sound EOV envisions acoustic time series being archived in institutional and/or national data centers, with an expansion of existing archives that are then linked via metadata records in OBIS.

Most global ocean observation programs that have established an international data access function feed data to the international center from national or institutional data management organizations. Most global data centers for observing systems that contribute to GOOS have more than one global data assembly center. Systems that could form the basis of a national and institutional set of data centers feeding into one or more international centers include the following:

- *Australia:* the Australian Ocean Data Network (AODN) and the Australian Antarctic Division Data Centre provide ocean sound data collected via national programs available through their dedicated data portals (https://portal.aodn.org.au; http://data.aad.gov.au)
- *Canada:* Ocean Networks Canada (https://oceannetworks.ca) provides access to data from Canadian hydrophones.
- *European Union:* European Union projects that include ocean acoustics manage their own acoustical data. One example is the INTAROS project, whose data can be accessed at https://portal-intaros.nersc.no/.
- *Germany:* The Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research is developing an open portal to underwater soundscapes, custom designed to provide standardized ocean sound level data collected worldwide and curated carefully for data quality (Thomisch et al. 2021), called the Open Portal to Underwater Soundscapes (OPUS).
- *Norway:* Norway provides acoustic data from its Lofoten Ocean Observatory. Additional acoustic data can also be found in the Norwegian Marine Data Center (https://www.nmdc.no/datasett).
- *United Kingdom:* The MEDIN data portal (https://medin.org.uk) serves marine data from across the UK, including ocean acoustic data. This portal allows one to search for UK ocean sound datasets ranging in duration from one day to 21 years, mostly in UK waters. A few of the datasets are available online; most require contacting the data holder.

- *United States:* The National Centers for Environmental Information (NCEI) of the U.S. National Oceanic and Atmospheric Administration (NOAA) archives and serves data from the NOAA Noise Reference Station Network, the NOAA-Navy Sanctuary Soundscape Monitoring Project (SanctSound), the NOAA National Marine Fisheries Service (NMFS) Ocean Acoustics Program, and Atlantic Deepwater Ecosystem Observing Network (ADEON) project. A map viewer/data access portal is available at https://maps.ngdc.noaa.gov/viewers/passive_acoustic/. See also Wall et al. (2021). Other U.S. systems for which data are freely available include the Integrated Ocean Observing System, the Aloha Cabled Observatory, the MBARI Cabled Observatory, and the Ocean Observatories Initiative. Data from U.S. ocean bottom seismometers are archived at the Incorporated Research Institutions for Seismology Data Management Center. Wall et al. (2021) describe potential U.S. contributions to managing passive acoustic data.

Ocean acoustic data from several national and institutional systems are available from the IQOE portal at https://www.iqoe.org/acoustic-data-portal.

Cabled hydrophones can provide real-time access to data, but underwater acoustic data from autonomous recorders are retrieved when the recorders are recovered, usually on an annual or shorter basis. Some of the derived data products may require real-time access to be useful. In particular, detection of transient events that require an immediate response, such as a tsunami alert, will require real-time processing and access. Few acoustic data are currently available in real-time mode, and real-time access will need to be built into the relevant measurement systems. Real-time access has been made available for some cabled hydrophones such as the Aloha Cabled Observatory (https://aco-ssds.soest.hawaii.edu/audio1.html). Most other applications require some delay for QA/QC and for processing the acoustic time series into the EOV formats.

The timing of data access and release will depend on whether hydrophones can transmit data through cables, satellite or phone links, or are autonomous recorders without telemetry capabilities, and whether there are national security or commercial restrictions for real-time access. Some GOOS applications require real-time data access, but other applications (e.g., tracking climate change, assessing biodiversity, and monitoring human use of the ocean.) do not require real-time data collection and access and therefore can receive data in a delayed mode.

The establishment of systems to serve acoustic data submitted by scientists from their nations requires standardized analysis programs. An example of current progress on this front involves the development of MANTA software to provide data for the derived data products of changes in sound levels and spectral probability density. This is accompanied by development of the Open Portal to Underwater Soundscapes (OPUS) being developed at the Alfred Wegener Institute to accept MANTA-processed data (https://epic.awi.de/id/eprint/53610/) and to host standardized ocean sound level data. OPUS will produce data products, such as nested, browsable stacks of spectrograms at different temporal resolutions, that will include the compiled MANTA data, as well as a description of details of the data processing, parameter-naming conventions, instructions for citing the data, and other information necessary to use the data according to FAIR standards. The PANGAEA repository (https://www.pangaea.de/) is increasingly being used to store acoustic data along with associated metadata and data processing reports, with data sets assigned a DOI to meet FAIR standards.

History suggests that long-term open access to historical data is best served by institutions where curation and maintenance of public availability to data is a core mission. Some government agencies maintain digital archives of data. For example, the International Council for the Exploration of the Sea (ICES) maintains a registry of impulse and continuous noise (https://www.ices.dk/data/data-portals/Pages/underwater-noise.aspx) that provides information required for European assessments of ocean sound, and governments may provide long-term support for these kinds of processed data that are required by regulations. However, other institutions are also worth considering for long-term curation. For example, the British Library (Ranft 2004) and the Macauley Library at Cornell University maintain digital sound archives of sounds including those from marine organisms. There is a lack of similar archives for ocean sound, but public or private institutions such as libraries and museums that maintain digital archives could be promising hosts for curating long-term digital collections of ocean sound.

Wall et al. (2021) have documented the benefits of centralized access for passive ocean acoustic data. This suggests the importance of establishing at least one global data assembly center for ocean sound. In order to become officially part of the GOOS international network, observing systems must satisfy a series of requirements overseen by the GOOS Observations Coordination Group (OCG). Observing networks currently fall into two categories: (1) Global Ocean Observing Network and (2) Emerging global observing networks. Networks wishing to affiliate with GOOS must demonstrate to the OCG that they fulfill most OCG network attributes and have a plan to remedy any deficiencies. New networks are considered by OCG and the GOOS Steering Committee and, if accepted, are first designated an Emerging Network, until the network demonstrates that all attributes have been met. However, observing systems do not need to be approved by the OCG to contribute to GOOS.

Most observing systems have a management structure that oversees the science and data management related to the observations. The World Meteorological Organization (WMO) and the Intergovernmental Oceanographic Commission (IOC) support the Observations Programme Support Centre (OceanOPS), which keeps an inventory of instruments and data centers and provides logistical support. A major contributor to the Ocean Sound EOV will be a global hydrophone network, which will require management and data functions different from most other EOVs. Emerging networks are those that have shown progress toward becoming an OCG network, but still need to demonstrate that they can achieve some of the attributes required of mature networks, albeit not all of them. If the global hydrophone system were to become an emerging global observing network, an international center for coordination of acoustic data would need to be developed that could then support wider contribution to the Ocean Sound EOV.

The volume of time series data from modern recorders and observatories is so large that ocean sound raises concerns about the capacity of digital archives to store ocean acoustic observations. In addition, some nations and research settings may constrain release of acoustic time series for some period of time after they are recorded. The global movement toward "Open Science" in all fields benefits marine acoustics, as long as the data sharing does not raise national security concerns, and we urge practitioners in our fields to adopt the open science culture, which has sped discovery in fields from astronomy and cancer biology to neuroscience and zoology. These factors suggest that the ocean sound community, including generators of data and users of data, should meet to discuss what data products need to be linked at the global level through GOOS, with data freely accessible and able to be turned into the derived data products listed in Figure 2-1. They will need to establish:

- How can the quality of calibrated data be controlled? What criteria are necessary for evaluation of data quality? Which organizations should coordinate or conduct the validation/evaluation process?
- What data are required for users to generate the derived data products?
- How can derived data products be developed that answer societal needs while addressing intellectual property and national security concerns?
- How rapidly do acoustic data need to be released for each data product? What are the obstacles, if any, to rapid enough release?
- How can time series be efficiently and effectively processed into the required forms of data?
- What institutional settings are best situated for long-term curation and archiving of these data and the derived data products?

Establishing clear responses and actions to these questions is a critical goal of this implementation plan. This will then need to be followed up with assessments of whether archives are developing in a way that meets the requirements of the EOV specification sheet. Different applications will require different standards. For example, data on long-term trends in ocean sound must have validated acoustic calibration, while data on acoustic detection of calls of different taxa may not require calibration of the pressure levels but will require validation that the detectors accurately categorize calls to the relevant taxonomic level.

# 6 GOVERNANCE AND FUNDING

## 6.1 Governance of existing GOOS networks

GOOS coordinates a set of observation networks through the GOOS Steering Committee and the GOOS Observations Coordination Group (OCG). Most of these networks are organized by platform rather than by sensor. Several examples include: (1) long-term time series from specific sites are provided by OceanSITES, (2) the Data Buoy Cooperation Panel (DBCP) oversees drifting and moored buoys, (3) the Argo Programme oversees profiling floats, and (4) GO-SHIP coordinates repeated ship-based transects. Most of these OCG networks have long been managed by intergovernmental bodies, such as the IOC-UNESCO and the World Meteorological Organization (WMO). Tracking of the assets of these different networks and international data access is maintained by the Observations Programme Support Centre (OceanOPS). Each network has a Technical Coordinator or Technical Secretary based at OceanOPS or IOC. These individuals serve as the coordinator for OceanOPS activities related to their system. These systems may also incorporate executive committees or other advisory groups that oversee the technical work of the systems and usually comprise members from countries that deploy observing assets for the system. The data from OCG networks are used in many applications relevant to society, such as port and harbor operations, health and safety, and weather and sea state predictions.

One way in which the Ocean Sound EOV can integrate ocean sound measurements into GOOS is to support the addition of acoustic sensors to some of these existing global ocean observing networks. As mentioned above, some Argo floats have been equipped with hydrophones (Yang et al. 2015; Riser et al. 2019). Other network, such as OceanSITES, GO-SHIP and DBCP, are candidates for adding acoustic sensors to GOOS. Adding acoustic sensors not only involves the cost of the additional instruments, but also requires demonstrating operability of the sensors on the platforms and may involve negotiating the added power and data storage/telemetry requirements. All of these tasks should be taken on by an Ocean Sound EOV group tasked with exploring the potential to add acoustic sensors to GOOS networks.

## 6.2 Funding for ocean acoustic observations

Observing systems are financially supported by funding for instruments, deployments, data analysis and management, and international coordination. These functions are mainly funded by individual nations. Management of national data is supported by participating nations, while international coordination of observing assets and providing data access is supported by one or more participating nations. International coordination of observing activities and in particular the collection of physical and biogeochemical observations (e.g., Argo) is often supported by one or a few nations, often in combination with national coordination of the activities of the host nation. This is not as common in the collection of biological and ecological observations. An important reason for developing this *Ocean Sound EOV Implementation Plan* is to provide a framework for acoustic observations that can lead to structured long-term international funding.

An important goal of the IQOE and of the Ocean Sound EOV is to bring together all communities that monitor sound in the ocean to harmonize methods from different scientific disciplines and share data in standardized formats to support observations of societal importance. The Ocean Sound EOV should engage industry, government agencies, military organizations, and research institutions to improve access to historical ocean sound data, to integrate new measurement systems for ocean sound into GOOS for understanding biological and physical ocean processes, and to be able to predict how these processes will change in the future.

Several ocean acoustic observation systems have been developed on international or national levels.

- The hydroacoustic monitoring system of the Comprehensive Nuclear-Test-Ban Treaty Organization (www.ctbto.org) has already been described as the most mature global ocean observation network, with stations carefully located for global coverage and real-time access to carefully calibrated acoustic data from cabled hydrophones. This system is operated under the auspices of the Comprehensive Nuclear-Test-Ban Treaty Organization. The data are used to detect undersea nuclear explosions. Real-time access is not publicly available, but delayed access can be negotiated with the CTBTO. While this system has many features required of GOOS networks, it does not allow completely open access to data.
- Sustained observation systems have also been supported with national funding for management and research purposes. National funding has been used to deploy hydrophones in Australia and the United States as parts of national ocean observing networks.

- Australia's Integrated Marine Observing System (IMOS), a GOOS regional alliance contributor, deployed and maintained ocean acoustic observations as part of its National Reference Station network at varying locations within its EEZ across the period 2008-2017. Various deployments of hydrophones throughout the Southern Ocean have also been undertaken by the Australian Antarctic Division and by researchers participating in the Australian Antarctic program. All IMOS ocean acoustic data and those data held in the Australian Antarctic Data Centre with supporting metadata are freely available.[8,9] IMOS ceased the deployment of hydrophones on its national reference stations in 2018 and it is currently unclear whether there will be future deployments. Deployments of hydrophones under the Australian Antarctic program are continuing but are sporadic and opportunistic in nature.
- In coastal areas of the United States, the U.S. National Oceanic and Atmospheric Administration (NOAA), Office of Naval Research, and National Park Service (NPS) have contributed to the deployment and maintenance of hydrophones in marine sanctuaries and other locations as part of the NOAA/NPS Ocean Noise Reference Station Network (NRS)[10] and the NOAA Navy Sanctuary Soundscape (SanctSound) Monitoring Project.[11] Data from these networks are openly available.[12] The SanctSound project ran from the fall of 2018 to the spring of 2022 and the agencies involved in the NRS intend to maintain the network as long as the U.S. government provides the necessary funding.

A large number of ocean acoustic sensors are also deployed at any given time as part of individual research projects, with short-term funding from national agencies, research institutes, and environmental NGOs. Ocean acoustics is typically used by different communities centered on very different topics such as national security, geophysics, or marine biology. Each group designs instruments and funds research programs to collect observations for their own purposes with little thought about multiple uses. These assets can contribute to measuring the Ocean Sound EOV, if they meet the standards for calibration, include required metadata and contribute data in a standardized format to a global data system that meets GOOS standards.

These examples illustrate some of the challenges in bringing varying contributions to a global network that builds sustained time series with adequate spatial coverage. Few of these efforts have developed systems to maintain open access to long-term observations of ocean sound but many efforts would benefit from long-term observations. Like other aspects of the GOOS EOVs, implementation, collection and archiving of observations of ocean sound will require the compilation of data from diverse equipment deployed by national governments, international organizations, commercial enterprises, and research scientists worldwide, and application of best practices in data quality control and archiving. Other contributors to the various GOOS EOVs can provide examples of how national observing assets can be integrated to produce data that can be combined into global products.

8 https://acoustic.aodn.org.au/acoustic/

9 https://data.aad.gov.au/datasets

10 https://www.pmel.noaa.gov/acoustics/noaanps-ocean-noise-reference-station-network

11 https://sanctuaries.noaa.gov/science/monitoring/sound/

12 https://maps.ngdc.noaa.gov/viewers/passive_acoustic/

Based on the information presented above regarding the availability of hydrophones on a variety of platforms, it is likely in the near and medium terms that the backbone of the Ocean Sound EOV will be observations collected by fixed autonomous and cabled hydrophones, with increasing augmentation by hydrophones deployed on mobile platforms. Added to long-term deployments will be short-term (weeks to one year) hydrophone deployments for research purposes that are more numerous than hydrophones used for sustained observations. Hydrophones on mobile platforms may be particularly useful in filling gaps in areas where it is technically difficult or expensive to deploy moored hydrophones. They may also provide less expensive ways to test the suitability of proposed sites for permanent ocean sound monitoring.

The initial implementation of the Ocean Sound EOV may mostly involve advocating for adding acoustic sensors to existing GOOS networks, coordinating existing acoustic observing assets for development as an emerging network, management of acoustic data, and creation of products based on these data. Ocean acoustic observations would benefit from adding acoustic sensors to existing platforms and stations such as OceanSITES and to developing infrastructure such as sensor clusters on undersea data transmission cables.

One of the aims in formalizing an Ocean Sound EOV is that it provides a recognized mechanism through which national agencies can make the case to provide sustained funding for ocean acoustic observations, as has occurred with other observing assets that contribute to other GOOS EOVs, such as Argo floats, tide gauges, and data buoys. The termination of funding for Australian and the 2022 end date for some U.S. acoustic observation networks highlights the need for national commitments to maintain long-term observations appropriate for GOOS. Products that are useful for research, management, and public outreach are critical for justification of continuous funding. Public awareness of observations collected as part of the Ocean Sound EOV will also be important for maintaining political pressure to continue governmental funding during changing budgetary environments.

## 6.3 GOOS models for supporting ocean acoustic observations

The mode of operation of existing components of the GOOS network could suggest options for financial support of the implementation and coordination of an Ocean Sound EOV. Examples include the following:

**Argo:** There is no central international funding for Argo float purchase or maintenance; each participating country funds its own floats. Many of the floats are deployed as part of specific research projects, with the resulting data made available through many mechanisms[13] and used in operational applications, in prediction, and in re-analysis products developed by many of the research institutions and agencies deploying floats. All Argo functions are supported financially and by in-kind contributions of staff by participating nations. The United States supports the international Argo office, and the two Global Data Assembly Centers are supported by France and the United States. Members of the Argo Science and Data Management teams generally support their own travel to team meetings.

13 See https://argo.ucsd.edu/data/

**GO-SHIP:** The Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) is a program of regular measurements of ocean physical and biogeochemical parameters along specific north-south and east-west transects throughout the global ocean (Sloyan et al. 2019). Transects have been repeated on an approximately decadal timescale since the 1990s, first by the World Ocean Circulation Experiment (WOCE), next by the Climate Variations (CLIVAR) program of the World Climate Research Programme (WCRP), and finally by GO-SHIP. Currently endorsed by the International Ocean Carbon Coordination Project (IOCCP) and the CLImate and ocean -VARiability, predictability and change (CLIVAR) project, the program develops formal international agreements for sustained, global, ship-based repeat hydrography with a decadal resolution, and develops sampling manuals and data syntheses. Research cruises have been funded by the participating nations, initially for the WOCE experiment, and growing into programs supporting longer term observations.

The Argo model may be useful for integrating support for many of the shorter term and more local deployments of ocean acoustic recordings into a longer term, broader scale research program. The GO-SHIP model may be useful for evolving existing global acoustic monitoring systems such as CTBTO and national regional acoustic monitoring networks, helping and/or supplementing them to support the kind of longer-term global network that meets GOOS requirements.

## 6.4 Public awareness efforts that can help build support for existing and new systems

Weller et al. (2019) argue that support for sustained ocean observations "needs increased engagement and coordination of the ocean observation science community with non-profits, philanthropic organizations, academia," government agencies and the commercial sector. The IQOE primarily involves the scientific community, but has focused on outreach to policymakers, industry representatives, the media, and other stakeholders (Tyack et al. 2015). Governance of the Ocean Sound EOV may require and will benefit from including a broad range of different communities. Data on sound in the ocean is important for marine industries whose production of sound is regulated, and for organizations concerned about ocean sound as a stressor for marine organisms. As described above, the derived data products are important for a broad array of user groups. The sounds of marine organisms have stimulated enormous public interest. The 1970 LP "Songs of the humpback whale" sold over 100,000 copies, and the launch of the global library of underwater biological sounds (Parsons et al. 2022) generated a flood of international reporting. Public fascination with ocean sounds can be harnessed to stimulate broader interest in observation of ocean sound. Implementing the Ocean Sound EOV will require similar outreach and involvement of communities that will use or be informed by the data products resulting from ocean sound observations.

## 6.5 Conclusion

Implementation of the Ocean Sound EOV will require at least four activities: (1) establishment of a coordination function for an international hydrophone network, (2) establishment of a QA/QC function for acoustic data, (3) coordinating and ensuring long-term availability of acoustic data records, and (4) capacity building and technology transfer. Each of these activities may be able to grow from ongoing IQOE working groups.

### 6.5.1 Coordination function for an international hydrophone network

Based on recent experience with other systems of observing assets (e.g., Argo, GO-SHIP), international coordination of the global set of non-military hydrophones will need to be spearheaded by interested scientists and national science agencies, rather than by GOOS or its sponsors. The IQOE has coordinated a list of existing acoustic observing systems which may be able to organize into an emerging ocean sound network for GOOS.

### 6.5.2 QA/QC of ocean acoustic data

Calibration of acoustic recording systems, development of validated reference data sets of sounds from different sources, and standardization of analysis methods are essential to make ocean acoustic measurements more comparable. The IQOE WGs on standardization and on marine bioacoustical standardization may be able to develop into an activity serving this function for ocean sound observations. QA/QC is not only required for the acoustic variables of sound pressure and particle motion, but also for the supporting variables shown in the left column of Figure 2.1. Different scientific communities and user groups will be required to curate and maintain these reference data sets on variables that affect sound propagation and on sound sources as diverse as snapping shrimp, fish, marine mammals, cracking ice, waves breaking, and earthquakes. Algorithms for detecting transient signals in ocean sound can be validated against reference data sets of signals of known origin. Regular conferences and workshops can facilitate this function. For example, the Detection, Classification, Localization and Density Estimation workshops (e.g., https://www.cetus.ucsd.edu/dclde/) provide reference data sets for different groups to test their algorithms in an open structured process. Investments in open-access validated reference data sets is essential for progress in development of detectors and automated analyses.

### 6.5.3 Management and access to ocean acoustic data

International management of ocean acoustic observations and data management could be overseen by an international steering team and data management committee for the network of underwater acoustic recording systems, with national coordinating committees being responsible for managing national observing resources and to make sure that national data are accessible via international digital acoustic data archives. There may also be value in working with marine industries, such as those using sound to survey the seafloor or hydrocarbon deposits below the seafloor, to explore sharing of historic recordings of ocean sound, particularly in resource rich areas where exploration has occurred. Several strong national efforts are underway, and the IQOE WG on Data Management and Access may be able to provide the starting point for the international steering team to establish long-term curation of these data in appropriate institutions.

### 6.5.4 Capacity building and technology transfer

The IQOE workshop on low-cost self-contained underwater acoustic recording systems showed that there is a strong interest internationally in systems capable of calibrated measurements suitable for GOOS applications and also for lower cost systems suitable for educational and citizen science applications. The ocean acoustic community contains many experts enthusiastic in driving the development of such systems. This activity should focus on linking those with strong interest with experts capable of developing the required technology and instructional materials to meet the demand.

# 7 PROPOSED TASKS TO IMPLEMENT OCEAN ACOUSTIC OBSERVATIONS FOR GOOS

This implementation plan proposes the following set of tasks to implement an Ocean Sound EOV that could contribute to GOOS.

## 7.1 Set up international coordination for observations from hydrophones and particle motion detectors

IQOE is working with operators of ocean acoustic measurement systems to establish a global network of hydrophones that could serve as the starting point for an emerging global ocean sound observation network to be considered by the GOOS OCG. The goal is by the end of IQOE to have a self-sustaining group of hydrophone operators with leadership that would oversee the hydrophone network with standards for calibration, signal analysis, and open data access to meet the requirements of the GOOS OCG. As described in Section 5.2, these networks usually have an executive or advisory committee and may require funding for a coordinator and travel. This network could be modeled on the international Argo system, for which the community raised support for a full-time project manager supported by a volunteer advisory committee. Support from a few national governments facilitate funding these needs for Argo. Tracking of metadata for the global set of more than 200 hydrophones is currently conducted by the IQOE Project Manager (https://www.iqoe.org/systems). It would be helpful for the operators of these systems to develop support for an office to assume responsibility for supporting tasks 7.2-7.5 below and making the case for their participation in an official international network of operators that could develop into an emerging Ocean Sound network for GOOS.

## 7.2 Maintain the existing global set of hydrophones and particle motion detectors and historic ocean sound datasets

An important step in implementing the Ocean Sound EOV will be to develop support for maintaining and extending the existing global set of hydrophones, based on existing operational and research systems. The first priority is to maintain existing measurement assets, especially those with long time series, and to ensure curation with QC of calibration and metadata and stable open-access archiving of historic datasets. This can be a challenge because operational systems may not have stable funding if national science budgets are cut. Many existing ocean acoustic measurement systems are funded through short-term research grants, and even long-term networks are vulnerable to termination of national funding. A critical part of this task will involve organizing users of these datasets to communicate the value of continuity of observations to funders of the networks.

## 7.3 Foster inclusion of particle motion sensors and their deployment systems where needed

This implementation plan focuses primarily on hydrophones that measure acoustic pressure. Many marine organisms detect the particle motion component of ocean sound. Understanding the effects of ocean sound on these organisms requires estimation of particle motion. There are some areas of ocean where it is possible to use acoustic pressure to estimate the magnitude of particle motion, but there are other areas near the sea surface or seafloor or in shallow water where particle motion must be measured directly. Nedelec et al. (2021) provide guidance on when particle motion should be measured along with pressure, and how to measure particle motion. The development of the Ocean Sound EOV in observation networks should follow this best practice guide as to when and how to include measurements of particle motion in ocean sound observations. Accelerometers on ocean bottom seismometers have also been used along with hydrophones to detect and locate low-frequency whale calls (Matias and Harris 2015), suggesting benefits for detecting particle motion along with acoustic pressure in some applications.

## 7.4 Review existing deployments of ocean acoustic sensors, identify gaps in coverage and propose how to mature them into a GOOS observation network

Chapter 4 describes how different uses of ocean sound may best be served by observing systems with different modes of deployment. For the emerging network of existing ocean acoustic sensors to mature into a GOOS observation network, each specific use will require a detailed effort to determine the locations and numbers of acoustic measurement stations and systems necessary to fulfil scientific and management needs of uses such as those described in Table 4-1. The usual approach to identify the density and locations of sensors for any ocean parameter is to model how the placement of sensors affects the ability to answer research and policy questions (e.g., Denvil-Sommer et al. 2021). For ocean sound, this would require bringing the ocean acoustic community together to identify current assets that might contribute to such a network and work together through a global modelling project or simulation experiment to determine the best placement and density of additional hydrophones for different research and management purposes. The set of hydrophones might include components that collect data on scales of hours to days (acoustic recording tags/buoys), weeks to months (Argo floats/gliders), and months to decades (moored hydrophones). Similar analyses may be required to estimate required observations for supporting variables on sound propagation and sound sources.

## 7.5 Develop standards for GOOS-compatible underwater acoustic recording systems and explore adding acoustic sensors to existing GOOS networks

The goal of adding acoustic recording systems to existing GOOS observation networks requires the development of underwater acoustic recording systems that are compatible with GOOS platforms. These systems must provide stable calibrated measurements of acoustic pressure or particle motion. When designing an acoustic recording system, it is important to consider the minimum and maximum ranges of frequency and sound levels that are required. Most modern acoustic recorders digitize the voltage output from the hydrophone and store the digital data. The sampling rate for digitizing the data must be at least twice the highest frequency of interest. The dynamic range (usually expressed in decibels or dB) of the recording should depend upon the faintest and loudest sounds that must be recorded faithfully. The more bits in the digital representation of each pressure sample that are measured and the lower the self-noise of the equipment, the higher the dynamic range. These acoustic recording systems must be tested for compatibility with existing GOOS observation networks. Systems to be deployed on autonomous platforms must be compact enough and use low-enough power to fit within existing space and battery capacities of the platforms. The high data rates of some acoustic systems and applications will also need to be compatible if they are integrated into data storage or telemetry of the observation networks. IQOE is working on establishing a working group for developing GOOS compatible underwater acoustic recording systems and validating their compatibility with existing GOOS observation networks.

## 7.6 Establish Working groups on calibration, standardizing data analysis, and data management

The Ocean Sound EOV requires standardized SI parameters and data formats. As discussed in Section 5.2, ocean acousticians and users of ocean sound should meet to discuss whether additional ocean acoustic standards are needed in addition to those inventoried by the IQOE Working Group on Standardization (IQOE Inventory of existing standards), develop plans for any new best practice guides that need to be developed for www.oceanbestpractices.org, and the best flow path from gathering of ocean sound data to producing reliable derived data products as quickly as needed by the users, with long-term open-access data archives. Section 5.2 describes a set of national data centers that already serve ocean acoustic data. The results of this meeting and working group should help ensure that data from each national or regional system are compatible for the creation of global ocean sound datasets. This working group should work with OBIS to establish whether and how OBIS can serve metadata linked to ocean acoustic data from national or regional centers.

## 7.7 Develop standardized open-access databases of ocean sound produced by known human, biotic, and abiotic sources

Abundant information exists about sources of ocean sound, but this information does not currently meet the GOOS requirements in terms of standardization and open access. Parsons et al. (2022) argue for the development of a database for biotic sources, and there are similar needs for abiotic and human sources. Users of this information globally would benefit from standardized open-access databases of sound produced by known human, biotic, and abiotic sources. While these data are not primary data for the Ocean Sound EOV, many of the derived data products will require maturation of databases of all of these sources of ocean sound. Just as museums maintain holotypes to define species, so a reference library of validated signatures of sound sources made under different conditions of propagation, background noise and habitat in the ocean is critical for some of the derived data products of the Ocean Sound EOV.

## 7.8 Develop low-cost underwater acoustic measurement systems for educational and citizen science applications

Deployments of ocean acoustic recorders in developing countries and providing students direct experience with underwater recordings is difficult because of the costs of acoustic measurement systems and moorings, and the narrow scope of experience in calibrating, deploying, and maintaining acoustic measurement systems. As part of the global expansion task, it will be necessary to identify acoustic measurement systems that could be widely deployed because they are inexpensive, durable, and easy to maintain and use. The IQOE held a virtual workshop on Low-Cost, Self-contained Underwater Acoustic Recording Systems on 13-14 December 2021 (https://www.iqoe.org/workshops/iqoe-workshop-low-cost-self-contained-underwater-acoustic-recording-systems). Presentations to the workshop introduced several initiatives for low-cost equipment that use less power, including digital acoustic loggers available for <$100, which had been set as a challenge for the workshop. They also included several innovative methods for calibrating hydrophones. An important task for expanding the observing network will be to provide training on calibration, deployment, and maintenance of observing equipment; processing of data; creation of products useful for local managers and scientists; and access to data through an international data portal. The Partnership for Observation of the Global Ocean (POGO) is leading activities to develop, deploy, and handle the data from less expensive ocean measurement systems, such as for temperature, and could work with IQOE on similar projects for acoustic devices. The IQOE is working on establishing task teams for low-cost underwater acoustic measurement systems, and for developing educational and citizen science applications for these devices.

## 7.9 Engage with industry and regulators along with ocean acoustic modelers to develop hindcast, nowcast and forecast ocean soundscape scenarios

Chapters 2 and 4 describe how measurements of ocean sound coupled with models of sound propagation and information about sound sources can be used to estimate soundscapes. An important application of ocean sound involves estimating potential changes to soundscapes based upon planned changes in human activities and/or expected changes in the distribution of natural sound sources and factors affecting sound propagation. These forecasts will be useful for seagoing industries and their regulators. Hindcasts to estimate soundscapes from earlier times may also be useful for understanding past changes in soundscapes. Results of these forecasts and hindcasts could affect critical decisions about planned activities, and they should be based upon the best science available. This challenging interdisciplinary task would be facilitated by a working group formed of industry, regulators, and ocean acoustic modelers along with the prime data collectors of the Ocean Sound EOV.

## 7.10 Reach out to policymakers, industry representatives, the media, and other stakeholders

The Ocean Sound EOV needs to include communities that will use or be informed by the data products resulting from ocean sound observations. This will help to ensure that the applications of ocean sound are the most relevant for the users of this information. Outreach to a broad range of different communities is also important to expand the user pool of ocean sound observations, and to increase public understanding of the importance of observations that are sustained over the long term. Observations of ocean sound are relevant for regional, national, and international organizations, including several that operate under the auspices of the UN: world ocean assessments, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), and the Intergovernmental Panel on Climate Change. Weller et al. (2019) propose establishing an Ocean Partnership for Sustained Observing early in the UN Decade of Ocean Science. The Ocean Sound EOV should take part in this partnership with international organizations to add the voice of ocean sound to the broader effort to sustain ocean observations.

## 7.11 Develop a self-sustaining observation network for the Ocean Sound EOV

GOOS assigned responsibility for the Ocean Sound EOV to the IQOE. The IQOE, which is currently responsible for the Ocean Sound EOV, has been planned as a decade-long program, and is scheduled for completion at the end of 2025. The years 2021-2030 have been designated as the United Nations Decade of Ocean Science for Sustainable Development. The Ocean Decade has approved a research program on the Maritime Acoustic Environment (UN-MAE), which aims to observe physical, biological and anthropogenic components of ocean sound at regional to global scales. Both programs should be able to help catalyze the formation of self-sustaining working groups of individuals, institutions, and nations that are involved in funding, making, and using ocean observations. IQOE and UN-MAE will help empower contributors to be part of the network, to guide standardization, to argue for stable long-term funding, and to provide data archive and exchange technology. The goal will be for the network and its working groups to be self-sustaining and able to deliver ocean sound observations into national/regional/global reporting mechanisms and to end users by the end of the Ocean Decade in 2030.

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# REFERENCES


An, C., Liu, P.L.F. 2014. Characteristics of leading tsunami waves generated in three recent tsunami events. *Journal of Earthquake and Tsunami* 8(03):1440001.

Andrew, R.K., Howe, B.M., Mercer, J.A., Dzieciuch, M.A. 2002. Ocean ambient sound: comparing the 1960s with the 1990s for a receiver off the California coast. *Acoustics Research Letters Online* 3(2):65-70.

Andrew, R.K., Howe, B.M., 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.

Aulanier, F., Simard, Y., Roy, N., Gervaise, C., 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.

Basan, F., Fischer, J.-G., Kühnel, D. 2021. Soundscapes in the German Baltic Sea before and during the Covid-19 pandemic. *Frontiers in Marine Science* 8:689860. DOI: 10.3389/fmars.2021.689860.

Bassett, C., Polagye, B., Holt, M., Thomson, J. 2012. A vessel noise budget for Admiralty Inlet, Puget Sound, Washington (USA). *The Journal of the Acoustical Society of America* 132(6):3706-19.

Baumgartner, M.F., Ball, K., Partan, J., Pelletier, L.-P., Bonnell, J., Hotchkin, C., Corkeron, P.J., van Parijs, S.M. 2021. Near real-time detection of low-frequency baleen whale calls from an autonomous surface vehicle: Implementation, evaluation, and remaining challenges. *The Journal of the Acoustical Society of America* 149:2950. DOI: 10.1121/10.0004817.

Bittencourt, L., Soares-Filho, W., de Lima, I.M.S., Pai, S., Lailson-Brito, J., Barreira, L.M., et al. 2018. Mapping cetacean sounds using a passive acoustic monitoring system towed by an autonomous Wave Glider in the Southwestern Atlantic Ocean. *Deep Sea Research Part I: Oceanographic Research Papers* 142:58–68. DOI: 10.1016/j.dsr.2018.10.006.

Bohnenstiehl, D.R., Lyon, R.P., Caretti, O.N., Ricci, S.W., Eggleston, D.B. 2018. Investigating the utility of ecoacoustic metrics in marine soundscapes. *Journal of Ecoacoustics* 2: #R1156L. DOI:10.22261/JEA.R1156L.

Brownlow, A., Davison, N., ten Doeschate, M. 2019. Scottish Marine Animal Stranding Scheme 2018 Annual Report, SRUC Wildlife Unit, Inverness. DOI: 10.31219/osf.io/qkcwg.

Burgess, W.C., Tyack, P.L., Le Boeuf, B.J., Costa, D.P. 1998. A programmable acoustic recording tag and first results from free-ranging northern elephant seals. *Deep-Sea Research Part II: Topical Studies in Oceanography* 45(7): 1327-1351.

Cauchy, P., Heywood, K.J., Merchant, N.D., Queste, B.Y., Testor, P. 2018. Wind speed measured from underwater gliders using passive acoustics. *Journal of Atmospheric and Oceanic Technology* 35:2305-2321. DOI: 10.1175/JTECH-D-17-0209.1.

Cauchy, P., Heywood, K.J., Risch, D., Merchant, N.D., Queste, B.Y., Testor, P. 2020. Sperm whale presence observed using passive acoustic monitoring from gliders of opportunity. *Endangered Species Research* 42: 133–149. DOI: 10.3354/esr01044.

Chérubin, L.M., Dalgleish, F., Ibrahim, A.K., Schärer-Umpierre, M., Nemeth, R.S., Matthews, A., et al. 2020. Fish spawning aggregations dynamics as inferred from a novel, persistent presence robotic approach. *Frontiers in Marine Science* 6:779. DOI: 10.3389/fmars.2019.00779.

Curtis, K.R., Howe, B.M., Mercer, J.A. 1999. Low-frequency ambient sound in the North Pacific: Long time series observations. *The Journal of the Acoustical Society of America* 106(6):3189-3200.

De Clippele, L.H., Risch, D. 2021. Measuring sound at a cold-water coral reef to assess the impact of COVID-19 on noise pollution. *Frontiers in Marine Science* 8:674702. DOI: 10.3389/fmars.2021.674702.

Denvil-Sommer, A., Gehlen, M., Vrac, M. 2021. Observation system simulation experiments in the Atlantic Ocean for enhanced surface ocean $pCO_2$ reconstructions. *Ocean Science* 17:1011–1030. DOI: 10.5194/os-17-1011-2021.

DeRuiter, S.L., Tyack, P.L., Lin, Y.T., Newhall, A.E., Lynch, J.F., Miller, P.J. 2006. Modeling acoustic propagation of airgun array pulses recorded on tagged sperm whales (*Physeter macrocephalus*). *The Journal of the Acoustical Society of America* 120(6):4100-4114.

Dreo, R., Bouffaut, L., Leroy, E., Barruol, G., Samaran, F. 2019. Baleen whale distribution and seasonal occurrence revealed by an ocean bottom seismometer network in the Western Indian Ocean. *Deep-Sea Research Part II-Topical Studies in Oceanography* 161132-144. DOI: 10.1016/j.dsr2.2018.04.005.

Dröge, S., Martin, D.A., Andriafanomezantsoa, R., Burivalova, Z., Fulgence, T.R., Osen, K., et al. 2021. Listening to a changing landscape: Acoustic indices reflect bird species richness and plot-scale vegetation structure across different land-use types in north-eastern Madagascar. *Ecological Indicators* 120:106929.

Dunn, C., Theriault, J., Hickmott, L., Claridge, D. 2021. Slower ship speed in the Bahamas due to COVID-19 produces a dramatic reduction in ocean sound levels. *Frontiers in Marine Science* 8:673565. DOI: 10.3389/fmars.2021.673565.

Dziak, R.P., Bohnenstiehl, D.R., Stafford, K.M., Matsumoto, H., Park, M., Lee, W.S., et al. 2015. Sources and levels of ambient ocean sound near the Antarctic Peninsula. *PloS One* 10(4):p.e0123425.

Erbe, C., Williams, R., Sandilands, D., Ashe, E. 2014. Identifying modeled ship noise hotspots for marine mammals of Canada's Pacific region. *PloS One* 9(3): e89820. DOI:10.1371/journal.pone.0089820

Erbe, C., McCauley, R., Gavrilov, A., Madhusudhana, S.K., Verma, A. 2016. The underwater soundscape around Australia. *Proceedings of Acoustics* 1:8-17.

Fisher, F.H., Simmons, V.P. 1977. Sound absorption in sea water. *The Journal of the Acoustical Society of America* 62(3):558-564.

Frantzis, A. 1998. Does acoustic testing strand whales? *Nature* 392(6671):29-29.

Fregosi, S., Klinck, H., Horning, M., Costa, D.P., Mann, D., Sexton, K., et al. 2016. An animal-borne active acoustic tag for minimally invasive behavioral response studies on marine mammals. *Animal Biotelemetry* 4(1): 1-15.

Gabriele, C.M., Ponirakis, D.W., Klinck, H. 2021. Underwater sound levels in Glacier Bay during reduced vessel traffic due to the COVID-19 pandemic. *Frontiers in Marine Science* 8:674787. DOI: 10.3389/fmars.2021.674787.

Harris, D.V., Miksis-Olds, J.L., Vernon, J.A., Thomas, L. 2018. Fin whale density and distribution estimation using acoustic bearings derived from sparse arrays. *The Journal of the Acoustical Society of America* 143(5):2980-93.

Harris, P., Sotirakopoulos, K., Robinson, S., Wang, L., Livina, V. 2019. A statistical method for the evaluation of long-term trends in underwater noise measurements. *The Journal of the Acoustical Society of America* 145(1):228-242.

Haver, S.M., Klinck, H., Nieukirk, S.L., Matsumoto, H., Dziak, R.P., Miksis-Olds, J.L. 2017. The not-so-silent world: Measuring Arctic, Equatorial, and Antarctic soundscapes in the Atlantic Ocean. *Deep Sea Research Part I: Oceanographic Research Papers* 122:95-104.

Haver, S.M., Gedamke, J., Hatch, L.T., Dziak, R.P., Van Parijs, S., McKenna, M.F., et al. 2018. Monitoring long-term soundscape trends in US Waters: the NOAA/NPS Ocean noise reference station network. *Marine Policy* 90:6-13.

Herring, P., Gaten, E., Shelton, P. 1999. Are vent shrimps blinded by science? *Nature* 398: 116. DOI: https://doi.org/10.1038/18142.

Howard, J., 2011. Fixed sonar systems: the history and future of the underwater silent sentinel. http://hdl.handle.net/10945/35007.

Howe, B.M., Miksis-Olds, J., Rehm, E., Sagen, H., Worcester, P.F., Haralabus, G. 2019a. Observing the oceans acoustically. *Frontiers in Marine Science* 6:426. DOI: 10.3389/fmars.2019.00426.

Howe, B.M., Arbic, B.K., Aucan, J., Barnes, C.R., Bayliff, N., Becker, N., et al. 2019b. SMART cables for observing the global ocean: science and implementation. *Frontiers in Marine Science* 6:424. DOI:10.3389/fmars.2019.00424.

Howe, B.M., Angove, M., Aucan, J., Barnes, C.R., Barros, J.S., Bayliff, N., et al. 2022. SMART subsea cables for observing the earth and ocean, mitigating environmental hazards, and supporting the blue economy. *Frontiers in Earth Science* 9:1465.

Johnson, M.P., Tyack P.L. 2003. A digital acoustic recording tag for measuring the response of wild marine mammals to sound. *IEEE Journal of Oceanic Engineering* 28(1):3-12.

Johnson, M., Madsen, P.T., Zimmer, W.M.X., de Soto, N.A., Tyack, P.L. 2006. Foraging Blainville's beaked whales (*Mesoplodon densirostris*) produce distinct click types matched to different phases of echolocation. *Journal of Experimental Biology* 209:5038–5050.

Johnson, M., de Soto, N.A., Madsen, P.T. 2009. Studying the behaviour and sensory ecology of marine mammals using acoustic recording tags: a review. *Marine Ecology Progress Series* 395:55-73.

Keeling, C.D., Bacastow, R.B., Bainbridge, A.E., Ekdahl Jr, C.A., Guenther, P.R., Waterman, L.S., et al. 1976. Atmospheric carbon dioxide variations at Mauna Loa Observatory, Hawaii. *Tellus* 28(6):538–551. DOI: 10.3402/tellusa.v28i6.11322.

Küsel, E.T., Siderius, M., Mellinger, D.K., Heimlich, S.L. 2015. Application of density estimation methods to datasets collected from a glider. *The Journal of the Acoustical Society of America* 138:1760. DOI: 10.1121/1.4933563.

Lamont, T.A., Chapuis, L., Williams, B., Dines, S., Gridley, T., Frainer, G., et al.2022. HydroMoth: Testing a prototype low-cost acoustic recorder for aquatic environments. *Remote Sensing in Ecology and Conservation* 8(3):362-378.

Loew, E.R.,1976. Light, and photoreceptor degeneration in the Norway lobster, *Nephrops norvegicus* (L.). *Proceedings of the Royal Society of London. Series B. Biological Sciences* 193(1110):31-44.

Looby, A., Cox, K., Bravo, S. Rountree, R., Juanes, F., Reynolds, L.K., et al. 2022. A quantitative inventory of global soniferous fish diversity. *Rev Fish Biol Fisheries* 32:581–595. DOI:10.1007/s11160-022-09702-1.

Ma, B.B., Nystuen, J.A., Lien, R.C. 2005. Prediction of underwater sound levels from rain and wind. *The Journal of the Acoustical Society of America* 117(6):3555-3565.

MacGillivray, A., de Jong, C. 2021. A reference spectrum model for estimating source levels of marine shipping based on Automated Identification System data. *Journal of Marine Science and Engineering* 9(4), 369.

Marques, T.A., Thomas, L., Ward, J., DiMarzio, N., Tyack, P.L. 2009. Estimating cetacean population density using fixed passive acoustic sensors: An example with Blainville's beaked whales. *The Journal of the Acoustical Society of America* 125(4):1982-1994.

Marques, T.A., Thomas, L., Martin, S.W., Mellinger, D.K., Ward, J.A., Moretti, D.J., et al. 2013. Estimating animal population density using passive acoustics. *Biological Reviews* 88:287–309. DOI: 10.1111/brv.1200.

Matias, L., Harris, D. 2015. A single-station method for the detection, classification and location of fin whale calls using ocean-bottom seismic stations. *The Journal of the Acoustical Society of America* 138:504-520.

Matsumoto, H., Haxel, J.H., Dziak, R.P., Bohnenstiehl, D.R., Embley, R.W. 2011. Mapping the sound field of an erupting submarine volcano using an acoustic glider. *The Journal of the Acoustical Society of America* 129(3):EL94-EL99.

Matsumoto, H., Bohnenstiehl, D.R., Tournadre, J., Dziak, R.P., Haxel, J.H., Lau, T.K., et al. 2014. Antarctic icebergs: A significant natural ocean sound source in the Southern Hemisphere. *Geochemistry, Geophysics, Geosystems* 15(8):3448-3458.

McCarthy, E., Moretti, D., Thomas, L., DiMarzio, N., Morrissey, R., Jarvis, S., et al. 2011. Changes in spatial and temporal distribution and vocal behavior of Blainville's beaked whales (*Mesoplodon densirostris*) during multiship exercises with mid-frequency sonar. *Marine Mammal Science* 27(3):E206-E226.

Meier, O. 2005. CTBTO releases test ban monitoring data for tsunami warning. *Arms Control Today* 35(3):39-40.

Mellinger, D.K., Clark, C.W. 2006. MobySound: A reference archive for studying automatic recognition of marine mammal sounds. *Applied Acoustics* 67(11-12):1226-1242.

Mellinger, D.K., Fregosi, S., Ampela, K. 2021. Large whale surveys off Southern California using passive acoustic gliders. *The Journal of the Acoustical Society of America* 150:A47. DOI: 10.1121/10.0007584.

Menze, S., Zitterbart, D.P., van Opzeeland, I., Boebel, O. 2017. The influence of sea ice, wind speed and marine mammals on Southern Ocean ambient sound. *Royal Society Open Science* 4:160370. DOI:10.1098/rsos.160370.

Merchant, N.D., Barton, T.R., Thompson, P.M., Pirotta, E., Dakin, D.T., Dorocicz, J. 2013. Spectral probability density as a tool for ambient noise analysis. *The Journal of the Acoustical Society of America* 133(4):262-267.

Merchant, N.D., Brookes, K.L., Faulkner, R.C., Bicknell, A.W., Godley, B.J., Witt, M.J. 2016. Underwater noise levels in UK waters. *Scientific Reports* 6(1):1-10.

Meyer, C.G., Burgess, W.C., Papastamatiou, Y.P., Holland, K.N. 2007. Use of an implanted sound recording device (Bioacoustic Probe) to document the acoustic environment of a blacktip reef shark (*Carcharhinus melanopterus*). *Aquatic Living Resources* 20(4): 291-298.

Miksis-Olds, J.L., Nichols, S.M. 2016. Is low frequency ocean sound increasing globally? *The Journal of the Acoustical Society of America* 139:501-511. DOI: 10.1121/1.4938237.

Miksis-Olds J.L., Dugan, P.J., Martin, S.B., Klinck, H., Mellinger, D.K., Mann, D.A., et al. 2021. Ocean sound analysis software for making ambient noise trends accessible (MANTA). *Frontiers in Marine Science* 8:703650. DOI: 10.3389/fmars.2021.703650.

Minello, M., Calado, L., Xavier, F.C. 2021. Ecoacoustic indices in marine ecosystems: a review on recent developments, challenges, and future directions. *ICES Journal of Marine Science* 78(9):3066-3074.

Mooney, T.A., Di Iorio, L., Lammers, M., Lin, T.-H., Nedelec, S., Parsons, M., et al. 2020. Listening forward: approaching marine biodiversity assessments using acoustic methods. *Royal Society Open Science* 7:201287. DOI: 10.1098/rsos.201287.

Moretti, D., Thomas, L., Marques, T., Harwood, J., Dilley, A., Neales, B.,et al. 2014. A risk function for behavioral disruption of Blainville's beaked whales (*Mesoplodon densirostris*) from mid-frequency active sonar. *PloS One* 9(1):e85064.

Myrberg, A.A. 1980. Fish bio-acoustics: its relevance to the 'not so silent world'. *Environmental Biology of Fishes* 5:297-304.

Myrberg Jr, A.A. 1990. The effects of man-made noise on the behavior of marine animals. *Environment International* 16(4-6):575-586.

Nedelec, S.L., Campbell, J., Radford, A.N., Simpson, S.D., Merchant, N.D. 2016. Particle motion: The missing link in underwater acoustic ecology. *Methods in Ecology and Evolution* 7:836–842.

Nedelec, S.L., Ainslie, M.A., Andersson, M.H., Cheong, S.H., Halvorsen, M.B., Linné, M., et al. 2021. *Best Practice Guide for Underwater Particle Motion Measurement for Biological Applications*. Technical report by Exeter University for the IOGP Marine Sound and Life Joint Industry Programme. DOI:10.25607/OBP-1726.

Nieukirk, S.L., Mellinger, D.K., Moore, S.E., Klinck, H., Dziak, R.P., Goslin, J. 2012. Sounds from airguns and fin whales recorded in the mid-Atlantic Ocean, 1999–2009. *The Journal of the Acoustical Society of America* 131(2):1102-1112.

Nystuen, J.A., Moore, S.E., Stabeno, P.J. 2010. A sound budget for the southeastern Bering Sea: Measuring wind, rainfall, shipping, and other sources of underwater sound. *The Journal of the Acoustical Society of America* 128:58-65. DOI: 10.1121/1.3436547.

Parsons, M.J., Salgado Kent, C.P., Recalde-Salas, A., McCauley, R.D. 2017. Fish choruses off Port Hedland, Western Australia. *Bioacoustics* 26(2): 135-152.

Parsons, M.J., Lin, T.-H., Mooney, T.A., Erbe, C., Juanes, F., Lammers, M., et al. 2022. Sounding the call for a global library of biological underwater sounds. *Frontiers in Ecology and Evolution.* DOI: 10.3389/fevo.2022.810156.

Payne, R., Webb, D. 1971. Orientation by means of long range acoustic signaling in baleen whales. *Annals of the New York Academy of Sciences* 188(1):110-141.

Pensieri, S., Bozzano, R., Nystuen, J.A., Anagnostou, E.N., Anagnostou, M.N., Bechini, R. 2015. Underwater acoustic measurements to estimate wind and rainfall in the Mediterranean Sea. *Advances in Meteorology* 612512. DOI: 10.1155/2015/612512

Picciulin, M., Bolgan, M., Codarin, A., Fiorin, R., Zucchetta, M., Malavasi, S. 2013. Passive acoustic monitoring of *Sciaena umbra* on rocky habitats in the Venetian littoral zone. *Fisheries Research* 145:76-81.

Pipatprathanporn, S., Simons, F.J. 2021. One year of sound recorded by a MERMAID float in the Pacific: Hydroacoustic earthquake signals and infrasonic ambient noise. *Geophysical Journal International* 228(1):193–212. DOI: 10.1093/gji/ggab296.

Popper, A.N., Hawkins, A.D. 2018. The importance of particle motion to fishes and invertebrates. *The Journal of the Acoustical Society of America* 143(1):470-488.

Prawirasasra, M.S., Mustonen, M., Klauson, A. 2021. The underwater soundscape at Gulf of Riga Marine-Protected Areas. *Journal of Marine Science and Engineering* 9(8):915.

Putland, R. L., de Jong, C.A.F., Binnerts, B., Farcas, A., Merchant, N.D. 2022. Multi-site validation of shipping noise maps using field measurements. *Marine Pollution Bulletin* 179:113733.

De Quirós Bernaldo, Y., Fernandez, A., Baird, R.W., Brownell, Jr R.L., Aguilar de Soto, N., Allen, D., et al. 2019. Advances in research on the impacts of anti-submarine sonar on beaked whales. *Proceedings of the Royal Society B* 286(1895):20182533.

Ranft R. 2004. Natural sound archives: past, present and future. *Anais da Academia Brasileira de Ciências* 76(2):456-60.

Rankin, S., Barlow, J. 2005. Source of the North Pacific "boing" sound attributed to minke whales. *The Journal of the Acoustical Society of America* 118(5):3346-3351.

Riser, S.C., Yang, J., Drucker, R. 2019. Observations of large-scale rainfall, wind, and sea surface salinity variability in the eastern tropical Pacific. *Oceanography* 32(2):42–49. DOI: 10.5670/oceanog.2019.211.

Robinson, S.P., Lepper, P.A., Hazelwood, R.A. 2014. *Good Practice Guide for Underwater Noise Measurement.* Teddington, England, National Measurement Office, Marine Scotland, The Crown Estate, 95pp. (NPL Good Practice Guide No. 133). DOI:10.25607/OBP-21.

Robinson, S.P., Harris, P.M., Wang, L., Cheong, S.H., Livina, V. 2019. Evaluation of long-term trends in deep-ocean noise in the Southern Ocean. In: *IEEE OCEANS 2019-Marseille*:1-6.

Robinson, S., Harris, P., Cheong, S.H., Wang, L., Livina, V., Haralabus, G., et al. 2023. Impact of the COVID-19 pandemic on levels of deep-ocean acoustic noise. *Scientific Reports* 13:4631. DOI: 10.1038/s41598-023-31376-3 https://doi.org/10.1038/s41598-023-31376-3.

Ryan, J.P., Joseph, J.E., Margolina, T., Hatch, L.T., Azzara, A., Reyes, A., et al. 2021. Reduction of low-frequency vessel noise in Monterey Bay National Marine Sanctuary during the COVID-19 pandemic. *Frontiers in Marine Science* 8:656566. DOI: 10.3389/fmars.2021.656566.

Sertlek, H.Ö., Slabbekoorn, H., ten Cate, C., Ainslie, M.A., 2019. Source specific sound mapping: Spatial, temporal and spectral distribution of sound in the Dutch North Sea. *Environmental Pollution* 247:1143-1157.

Slabbekoorn, H., Bouton, N., van Opzeeland, I., Coers, A., ten Cate, C., Popper, A.N. 2010. A noisy spring: the impact of globally rising underwater sound levels on fish. *Trends in Ecology & Evolution* 25(7):419-27.

Sloyan, B.M., Wanninkhof, R., Kramp, M., Johnson, G.C., Talley, L.D., Tanhua, T., et al. 2019. The Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP): A platform for integrated multidisciplinary ocean science. *Frontiers in Marine Science* 6:445. DOI: 10.3389/fmars.2019.00445.

Soule, D.C., Wilcock, W.S.D. 2013. Fin whale tracks recorded by a seismic network on the Juan de Fuca Ridge, Northeast Pacific Ocean. *The Journal of the Acoustical Society of America* 133:1751-1761.

Sousa-Lima, R.S., Norris, T.F., Oswald, J.N., Fernandes, D.P. 2013. A review and inventory of fixed autonomous recorders for passive acoustic monitoring of marine mammals. *Aquatic Mammals* 39(1):23-53.

Southall, B.L., Finneran, J.J., Reichmuth, C., Nachtigall, P.E., Ketten, D.R., Bowles, A.E., et al. 2019. Marine mammal noise exposure criteria: Updated scientific recommendations for residual hearing effects. *Aquatic Mammals* 45(2):125-232.

Spaulding, E., Robbins, M., Calupca, T., Clark, C.W., Tremblay, C., Waack, A., et al. 2009. An autonomous, near-real-time buoy system for automatic detection of North Atlantic right whale calls. In: *Proceedings of Meetings on Acoustics* 6(1):010001.

Sueur, J., Pavoine, S., Hamerlynck, O., Duvail, S. 2008. Rapid acoustic survey for biodiversity appraisal. *PloS ONE* 3:e4065. DOI: 10.1371/journal.pone.0004065.

Sueur, J., Farina, A., Gasc, A., Pieretti, N., Pavoine, S. 2014. Acoustic indices for biodiversity assessment and landscape investigation. *Acta Acustica united with Acustica* 100(4):772-781. DOI: 10.3813/AAA.918757.

Testor, P., de Young, B., Rudnick, D.L., Glenn, S., Hayes, D., Lee, C.M., et al. 2019. OceanGliders: A component of the integrated GOOS. *Frontiers in Marine Science* 6:422. DOI: 10.3389/fmars.2019.00422.

Thomisch, K., Flau, M., Heß, R., Traumueller, A., Boebel, O. 2021. OPUS – An Open Portal to Underwater Soundscapes to explore and study sound in the global ocean, 5th Data Science Symposium, virtual meeting, 22 January 2021.

Thompson, P.O., Friedl, W.A. 1982. A long term study of low frequency sounds from several species of whales off Oahu, Hawaii. *Cetology* 45:1–19.

Thomson, D.J.M., Barclay, D.R. 2020. Real-time observations of the impact of COVID-19 on underwater noise. *The Journal of the Acoustical Society of America* 147:3390. DOI: 10.1121/10.0001271.

Tyack, P.L. 2008. Implications for marine mammals of large-scale changes in the marine acoustic environment. *Journal of Mammalogy 89*(3):549-558.

Tyack, P.L., Frisk, G., Boyd, I., Urban, E., Seeyave, S. 2015. International Quiet Ocean Experiment Science Plan. https://iqoe.org/sites/default/files/files/IQOE_Science_Plan-Final.pdf.

Tyack, P.L., Thomas, L., Costa, D.P., Hall, A.J., Harris, C.M., Harwood, J., et al. 2022. Managing the effects of multiple stressors on wildlife populations in their ecosystems: developing a cumulative risk approach. *Proceedings of the Royal Society B* 289:20222058.

United Nations. 2021. The Second World Ocean Assessment. United Nations, New York.

Van Parijs, S.M., Clark, C.W., Sousa-Lima, R.S., Parks, S.E., Rankin, S., Risch, D., et al. 2009. Management and research applications of real-time and archival passive acoustic sensors over varying temporal and spatial scales. *Marine Ecology Progress Series* 395:21-36.

Wall, C.C., Haver, S.M., Hatch, L.T., Miksis-Olds, J. 2021. The next wave of passive acoustic data management: How centralized access can enhance science. *Frontiers in Marine Science* 873.

Warren, J.D., Ainslie, M.A., Miksis-Olds, J.L., Martin, B., Heaney, K.D. 2018. *ADEON Calibration and Deployment Good Practice Guide. Version 1.0.* Technical report by Stony Brook University for ADEON Prime Contract No. M16PC00003.

Weller, R.A., Baker, D.J., Glackin, M.M., Roberts, S.J., Schmitt, R.W., Twigg, E.S., et al. 2019. The challenge of sustaining ocean observations. *Frontiers in Marine Science* 6:105. DOI: 10.3389/fmars.2019.00105.

Wenz, G.M. 1964. Curious noises and the sonic environment in the ocean. In Marine Bio-Acoustics, edited by W. N. Tavolga (Pergamon, New York), pp. 101–119.

Wilkinson, M., Dumontier, M., Aalbersberg, I. Appleton, G., Axton, M., Baak., A., et al. 2016. The FAIR guiding principles for scientific data management and stewardship. *Scientific Data* 3:160018. DOI: 10.1038/sdata.2016.18.

Wong, A.P.S., Wijffels, S.E., Riser, S.C. Pouliquen, S., Hosoda, S., Roemmich, D., et al. 2020. Argo Data 1999–2019: Two million temperature-salinity profiles and subsurface velocity observations from a global array of profiling floats. *Frontiers in Marine Science* 7. DOI: 10.3389/fmars.2020.00700.

Wu, W., Zhan, Z., Peng, S., Ni, S., Callies, J. 2020. Seismic ocean thermometry. *Science* 369(6510):1510-1515.

Yang, J., Riser, S.C., Nystuen, J.A., Asher, W.E., Jessup, A.T. 2015. Regional rainfall measurements using the passive aquatic listener during the SPURS field campaign. *Oceanography* 28(1):52-61.

Zeddies, D.G., Fay, R.R., Alderks, P.W., Shaub, K.S., Sisneros, J.A. 2010. Sound source localization by the plainfin midshipman fish, *Porichthys notatus*. *The Journal of the Acoustical Society of America* 127:3104–3113.

Zhan, Z. 2019. Distributed acoustic sensing turns fiber-optic cables into sensitive seismic antennas. *Seismological Research Letters* 91:1–15. DOI: 10.1785/0220190112.

Zhou, H., Zeng, Z., Lian, L. 2018. Adaptive re-planning of AUVs for environmental sampling missions: A fuzzy decision support system based on multi-objective particle swarm optimization. *International Journal of Fuzzy Systems* 20(2):650-671.

# APPENDIX I. IQOE OCEAN SOUND EOV IMPLEMENTATION PLAN COMMITTEE

## Members

Peter Tyack, chair (UK)

Tom Akamatsu (Japan), Olaf Boebel (Germany), Lucille Chapuis (UK), Elisabeth Debusschere (Belgium), Christ de Jong (Netherlands), Christine Erbe (Australia), Karen Evans (Australia), Jason Gedamke (USA), Tess Gridley (South Africa), Georgios Haralabus (Austria), Reyna Jenkins (Canada), Jennifer Miksis-Olds (USA), Hanne Sagen (Norway), Frank Thomsen (Denmark), Karolin Thomisch (Germany)

## Liaisons

Patricia Miloslavich (SCOR)
Sophie Seeyave (POGO)

## Staff

Ed Urban (IQOE)

## Tasks of Committee

Write an implementation plan for the Ocean Sound Essential Ocean Variable, based on guidelines from the Global Ocean Observing System (GOOS).

Obtain input from IQOE working groups, and the global ocean acoustics and bioacoustics community to create the implementation plan, through online surveys, in-person workshop(s), and/or other means.

Interface with the GOOS Biology and Ecosystems Panel regarding the committee's work.

Report to the IQOE Science Committee and sponsors (SCOR and POGO)

# APPENDIX II. RECOMMENDATIONS FOR PROCESSING METRICS FROM THREE INTERNATIONAL WORKSHOPS FOCUSED ON SOUNDSCAPES AND LONG-TERM TRENDS IN OCEAN SOUND (FROM MIKSIS-OLDS ET AL. 2021)



| Processing metrics | | | | | |
|---|---|---|---|---|---|
| **Duty cycle (sampling period)** | **Temporal averaging window for SPL percentiles** | **Temporal unit for SPL statistics** | **SPL percentiles** | **Frequency analysis bandwidth** | **Total frequency bandwidth** |
| **2014 Joint IWC/IQOE/NOAA/ONR/TNO Workshop [1]** | | | | | |
| Minimum:<br>1 min/hr | Minimum:<br>1 min | Minimum:<br>1d<br>Optimum: 1 mon, seasonal, 1 yr | Minimum: 1<br>0, 25, 50, 75, 90% | Minimum:<br>Decidecade bands (1/3 octave base-10 bands) | Minimum:<br>10 Hz — 1 kHz decidecade bands |
| **2018 COL Ocean Sound Workshop [2]** | | | | | |
| Minimum:<br>2 min/hr with minimum 30 s contiguous recording time | Minimum:<br>30 s | Minimum:<br>1d<br>Optimum:<br>1 hr | Minimum:<br>10, 25, 50, 75, 90% | Minimum:<br>Decidecade bands (1/3 octave base-10 bands) | Minimum:<br>1 Hz bands at 1 s resolution over full frequency of recordings<br>Optional: 10 Hz bands at 0.2 s resolution and 100 Hz bands at 0.01 s resolution |

| Processing metrics | | | | | |
|---|---|---|---|---|---|
| **Duty cycle (sampling period)** | **Temporal averaging window for SPL percentiles** | **Temporal unit for SPL statistics** | **SPL percentiles** | **Frequency analysis bandwidth** | **Total frequency bandwidth** |
| **2019 IQOE Standards Workshop [3]** | | | | | |
| Minimum: Sufficient data to calculate percentiles with minimum 60s contiguous recording time<br>Optimum: >5 min per hr, spread evenly over the hr | Minimum: 1 min<br>Optimum: 1 s and 1 min | Minimum: 1 mon<br>Optimum: 1 hr, 1 d, 1 yr | Minimum: 10, 25, 50, 75, 90%<br>Optional: Include 5 and 95%<br>Optimum: Full CDF in 1% steps | Minimum: Decidecade bands (1/3 octave base-10 bands)<br>Optional: 1 Hz<br>Optional: Broadband calculated from decidecade bands | Minimum: 10 Hz — 1 kHz decidecade bands<br>Optimum: 10 Hz- 1 kHz in 1 Hz bands, 10 Hz-20 kHz in decidecade bands, optional up to max recording frequency |

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