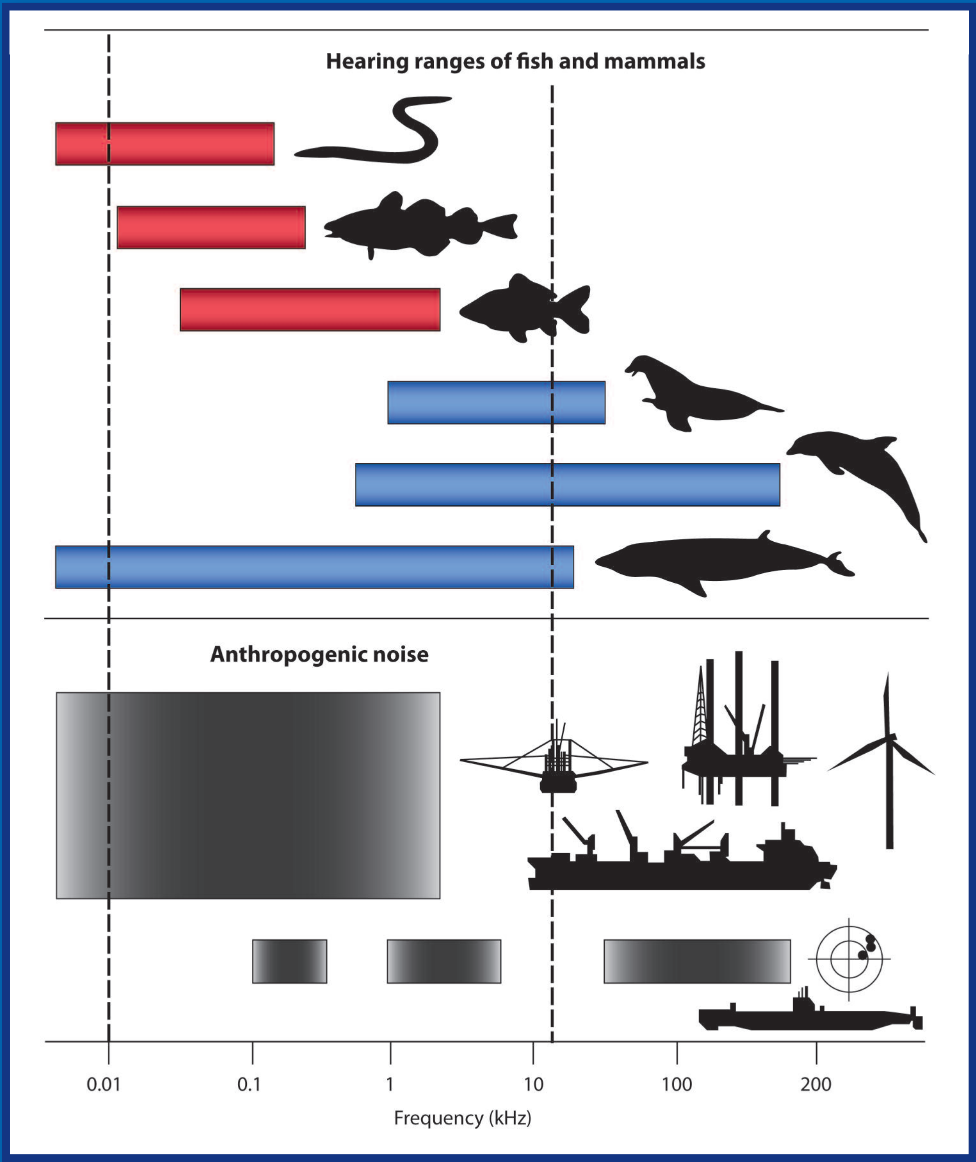
# INTERNATIONAL QUIET OCEAN EXPERIMENT

IQOE
International Quiet Ocean Experiment

## Science Plan





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International Council for Science
SCOR
Scientific Committee on Oceanic Research

pogo
Partnership for Observation of the Global Oceans

# International Quiet Ocean Experiment
# Science Plan

**Editors:** Peter Tyack, George Frisk, Ian Boyd,
Ed Urban, Sophie Seeyave

# Preface

This Science Plan for an International Quiet Ocean Experiment (IQOE) is the result of a series of discussions that started at the joint meeting of the Scientific Committee on Oceanic Research (SCOR) and the Ocean Studies Board of the U.S. National Research Council in October 2008 at the Woods Hole Oceanographic Institution. At that meeting, Jesse Ausubel of the Alfred P. Sloan Foundation posed the question about what might be observed in the behavior of animals in the ocean if all human-generated sound in the ocean were stopped for some period. Ausubel expanded on his ideas in a November 2009 article in *SEED Magazine*:

> *I propose that scientists, environmentalists, and maritime industries organize an International Quiet Ocean Experiment in which humans refrain from adding noise to the oceans for a few hours. Because of the speed sound spreads in sea water, we might, fortunately, need to turn down the volume globally for only four hours or so to achieve a great diminuendo. During this time researchers would observe the behavior of many forms of life in the ocean that might respond to the quiet change.* (JH Ausubel. Broadening the scope of global change to include illumination and noise. *SEED Magazine* 23 Nov. 2009)

Through funding from the Sloan Foundation, Ausubel helped SCOR and the Partnership for Observation of the Global Oceans (POGO) convene an international workshop of ocean acousticians and marine mammal scientists at the University of Rhode Island (URI, USA) in October 2010, led by Ian Boyd (University of St. Andrews, UK) and George Frisk (Florida Atlantic University/Woods Hole Oceanographic Institution, USA). Participants at the URI meeting concluded that, although it was probably not feasible to turn off sound in the ocean for any significant period, an international project on sound in the ocean and its effects on marine organisms is needed to help document ocean sound as a form of global change with widespread impacts. The results of the URI meeting were presented in a paper in *Oceanography* magazine (Boyd et al. 2011. An International Quiet Ocean Experiment. *Oceanography* 24(2):174–181, doi:10.5670/oceanog.2011.37.)

One conclusion of the URI meeting was that it would be important to gather ideas and input from the broader community of scientists, navies, industry, and others at an open meeting. The Intergovernmental Oceanographic Commission hosted an open science meeting at its headquarters in Paris, France, in August 2011. This Science Plan is a distillation of the discussions at that meeting.

The scientific community, SCOR, and POGO owe a debt of gratitude to Jesse Ausubel, the Alfred P. Sloan Foundation, the Intergovernmental Oceanographic Commission, and academic and governmental institutions that made this Science Plan possible. We also thank Ed Urban (SCOR Executive Director) and Sophie Seeyave (POGO Executive Director) for the excellent staff support they have provided in the development of this IQOE Science Plan.

Peter Burkill
SCOR President

Karen Wiltshire
POGO Chair

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*Cover figure from Slabbekoorn, H., N. Bouton, I. van Opzeeland, A. Coers, C. ten Cate, and A.N. Popper. 2010. A noisy spring: The impact of globally rising underwater sound levels on fish.* Trends in Ecology & Evolution *25:419-427. doi:10.1016/ j.tree.2010.04.005. Permission for reuse granted by* Trends in Ecology and Evolution.
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# Chapter 1
# Executive Summary

The International Quiet Ocean Experiment (IQOE) will create an international program of research, observation, and modeling to better characterize ocean sound fields and to promote understanding of the effects of sound on marine life. Our current knowledge is inadequate in relation to the effects of anthropogenic sound[1] on marine life; the resulting scientific uncertainty makes it difficult to balance the need for precaution in protecting marine ecosystems against the potentially large costs to socially important activities such as commercial shipping, offshore energy exploration and development, and military readiness.

A central feature of the IQOE will be an International Year of the Quiet Ocean (IYQO), which will focus the participating scientific, industrial, environmental, and naval communities on the goal of an intense period of scientific activity, coordinated across regions to create a global program. The IYQO will raise awareness of the effects of sound in the ocean within the participating communities and in the public realm. The IQOE aims to study effects of sound from an ecosystem perspective and longer time scale than most ongoing research. The project will focus broadly on soundscapes, defined by acoustic ecologists as all the sounds present in a habitat.

The IQOE will address five fundamental questions:

1. How have human activities affected the global ocean soundscape compared with natural changes over geologic time?
2. What are the current levels and distribution of anthropogenic sound in the ocean?
3. What are the trends in anthropogenic sound levels across the global ocean?
4. What are the current effects of anthropogenic sound on important marine animal populations?
5. What are the potential future effects of sound on marine life?

The IQOE is a response to evidence of increasing sound levels in the ocean from human activities. The human contribution to ocean sound has increased during the past few decades and anthropogenic sound has become the dominant component of marine sound in some frequency bands and geographic regions. Anthropogenic sound levels will increase as the ocean becomes more industrialized, thus making the measurement of ocean sound fields an important tool for assessing industrial presence in the ocean.

Sound is an important factor in the lives of many marine organisms. Evidence is accumulating that human-generated sound in the ocean is approaching levels that cause negative effects on marine life. Certain species already show symptoms of the effects of sound. Although some of these effects are acute, such as lethal strandings of beaked whales exposed to naval sonar, chronic sublethal effects may be more prevalent and therefore more important for populations, but are difficult to measure.

The IQOE will mobilize the participating communities to investigate sound in the ocean in a way that will be useful for management of sound sources to mitigate harm to marine life. The IQOE will (1) ensure that the measurement of the sound field becomes an integrated part of global ocean observations; (2) develop a global approach to investigating ocean sound, engaging the worldwide community of ocean scientists; (3) support innovation in passive ocean observing systems to detect, classify, and track marine organisms;

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[1] *Throughout this document we usually use the term "sound" instead of the term "noise"; the term "noise" is used when the source of sound cannot be identified, or in contexts emphasizing the contrast between a "signal" and background "noise."*

(4) support data management and the development of data standards; (5) develop models of how sound travels in the ocean; (6) support the planning and implementation of regional experiments; and (7) ensure constructive engagement with industry, regulators, nongovernmental organizations, and the public. To achieve these goals, the activities of the IQOE are planned around four themes:

**Theme 1 - Ocean Soundscapes:** Projects carried out under Theme 1 will describe *ocean soundscapes* from regional to global scales. This theme will include identification of the primary sound sources that contribute to each soundscape, empirical modeling of components of each soundscape, modeling of acoustic propagation, and validation of these models using ocean observation systems. This theme will be the main focus of efforts to measure trends in ocean sound levels and to define sound budgets within regions. It will also investigate soundscape diversity and examine the concept that the conservation of soundscapes may be an appropriate objective for integrated management of the marine environment.

**Theme 2 - Effects of Sound on Marine Organisms:** Theme 2 includes projects designed to plan and carry out experiments to study *the effects of sound on marine organisms.* This may include experiments to make regions quieter and to observe the responses of marine organisms to quieting. This theme will include the use of planned experiments as well as opportunistic studies using post hoc statistical modeling to test for effects. This theme is the main vehicle through which the biological significance of sound will be assessed and, where possible, this will be focused on estimating dose–response relationships so that assessments of the effects of sound can be predictive, with special emphasis on the effects of sound on populations and ecosystems. Much of this theme will rely on the use of a small set of representative species.

**Theme 3 - Observations of Sound in the Ocean:** *Observing sound in the ocean* will be the focus of work done under Theme 3 to coordinate and standardize existing acoustic observing systems, while adding sound measurements to existing and future observing systems, and to encourage technical innovation in the measurement of sound. This theme will develop data standards—where these do not already exist—and will promote observation of the key biological and physical variables. Much of the data management needed by the IQOE will be managed from within this theme.

**Theme 4 – Industry and Regulation:** Theme 4 develops the methodology for noise monitoring within regulatory regimes. This theme will include efforts to examine the operational management of sound in the ocean through risk analysis by, among other approaches, defining appropriate thresholds for disturbance, damage to marine life, and harm to marine ecosystems. It will also help regulators to measure compliance, and industry to maintain its activities, by providing innovative solutions to problems presented by regulation. This theme will integrate and apply the results from the other three themes.

Each of these four themes is important in preparations for the IYQO.

The IQOE will be implemented under the governance of the Scientific Committee on Oceanic Research (SCOR) and the Partnership for Observation of the Global Oceans (POGO). A Scientific Steering Committee will manage the project with the support of a secretariat. Working groups will be established to ensure that IQOE themes are implemented and to plan and implement particular activities. The Steering Committee will be responsible for international planning and coordination of contributing national activities funded from national sources over a period of at least 10 years. The IQOE will plan a series of workshops in its first three years, which will lay the foundation for IQOE implementation. Particular emphasis in the early years of the project will be given to characterizing global trends in ocean sound, gaining access to existing long time series of ocean sound, planning studies of effects, specifying standards for observations and experimentation, designing a data management system, and planning for pilot studies. As with other international research projects, the sponsors will seek funding for international planning and implementation, whereas it is expected that the national scientific communities interested in IQOE-related research and observations will solicit research funding from traditional national sources.

# Chapter 2
# Introduction and Overview

## 2.1 Purpose of the document

Underwater sound is important for many marine organisms. In general, marine species are more likely than terrestrial organisms to rely on sound to support life functions because the ocean is relatively opaque to light and is relatively transparent to sound. Ocean sound has many natural components, including naturally occurring events such as storms and breaking waves, the fracturing of sea ice, subsurface volcanoes and seismic activity, along with the calls and other sounds produced by a great variety of marine species. In the mid-19th century a new source of sound began to fill the ocean, driven by the rapid spread of mechanical propulsion in the shipping industry (Figure 2.1).

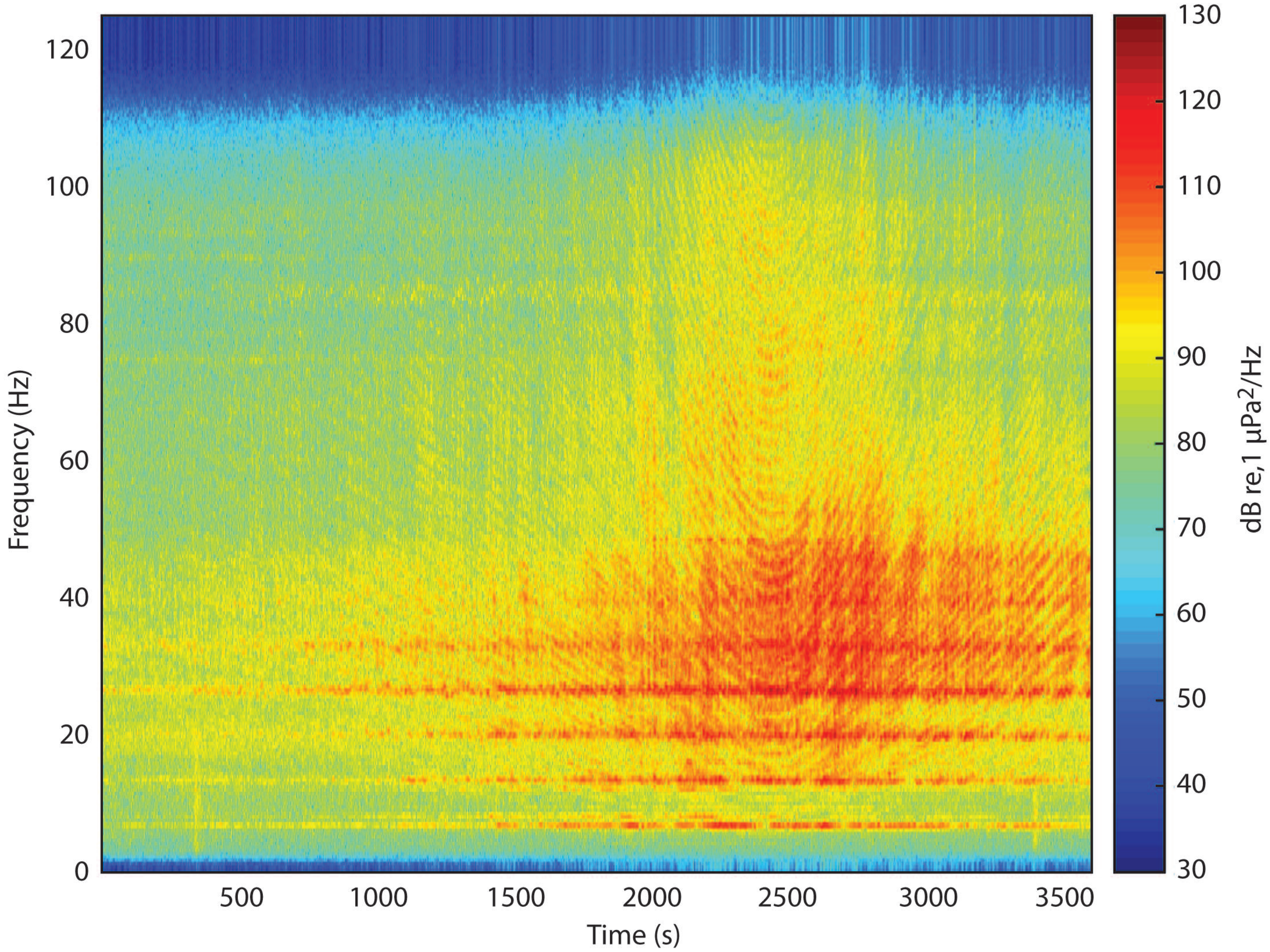
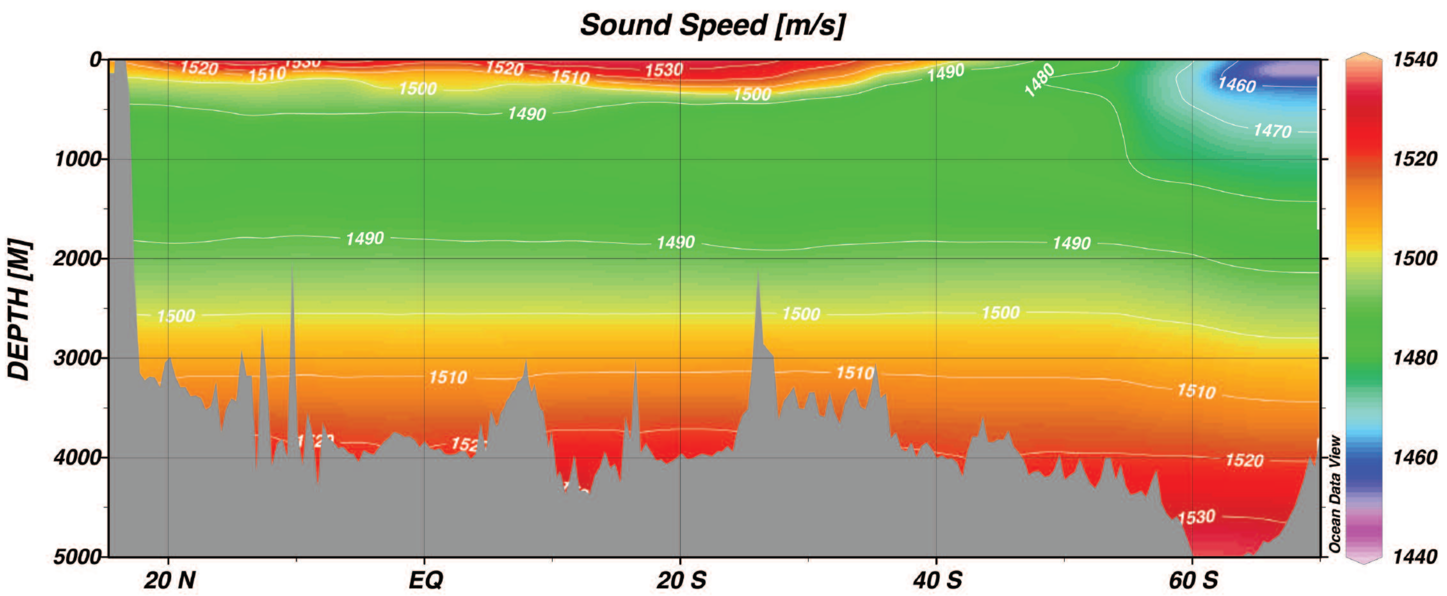



**Figure 2.1.** *Sound spectrogram of a large vessel passing by the Cape Leeuwin CTBTO observatory off southwestern Australia. Image courtesy of Centre for Marine Science and Technology, Curtin University, Perth, Western Australia.*

This human dimension to sound in the ocean is set against a backdrop of a complex natural sound field. For example, the deep ocean environment creates a sound channel (the SOFAR channel[2]) by which low-frequency acoustic waves can propagate over large distances, sometimes hundreds of kilometers and often much further (Figure 2.2). The multiple complex pathways taken by this sound affect the final received levels. When sound is averaged through time at the receiver, this provides an integrated signal defined by the relative locations of all the sound producers, the architecture of the ocean basin, and the properties of the water through which the sound has passed.



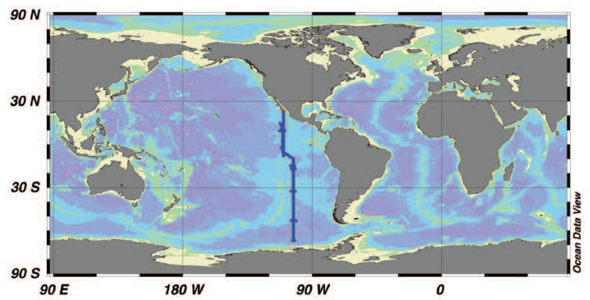




**Figure 2.2.** *Sound velocity section from hydrographic station (CTD) data collected across the Pacific Ocean (top) and map of the region showing the location of the hydrographic section (left). From Boebel et al. (2009). Used with permission from O. Boebel.*

The level of sound in the ocean may be linked to the global economy (Frisk, 2012). This is because most human activities in the ocean produce sound and many of these are increasing, including offshore construction, oil and gas exploration, fisheries, and recreational boating. Intense sound can have acute impacts on some animal life and it is assumed that low levels of continuous sound may lead to chronic effects, but little is known about the true extent of these chronic effects and whether they are likely to be a problem. However, if human activities resulting in increasing ocean sound levels continue on their current trajectory, they are likely to exceed thresholds of disturbance more often and in an increasing number of locations. Consequently, we can infer that chronic effects on marine life are likely to increase. This document develops the template for a global research project that will

[2] *The SOFAR channel is a horizontal layer of the ocean where sound speed is the slowest, because of the effects of temperature and pressure. Sound refracts toward areas of slower speed, so that sound, particularly low-frequency sound, can concentrate in this layer. In Figure 2.2, the SOFAR channel is roughly shown in green in the midlatitudes, with a shoaling (blue and purple colors) at higher latitudes.*

resolve the extent and significance of these effects and help to suggest mitigation approaches.

Human activity also has the potential to affect the levels of sound in the ocean in less direct ways. Intensive whaling and fishing have removed some biological producers of underwater sound, and global warming is altering the geographical distribution of other organisms. Some investigators have estimated that ocean warming has increased the strength and frequency of tropical storms (Knutson et al., 2010), which produce sound associated with rain, lightning, and breaking waves, and may influence the patterns of ice breaking in the polar regions. Even changes in the acidity of the ocean as it absorbs $CO_2$ affects its acoustic properties (Hester et al., 2008; Udovydchenkov et al., 2010), although there is still discussion of the magnitude of potential effects.

A scientific analysis of adverse effects from anthropogenic sound in the ocean is challenging because of the wide range of acoustic sources; variations in frequency, intensity, and occurrence; and the complexity of acoustic propagation, especially in strongly stratified and shallow waters. Even more significant is our ignorance of how animals respond behaviorally and physiologically to sound. Tackling the scientific problem of understanding underwater sound and its effects on organisms requires new interdisciplinary and international collaboration, and this document sets out how we are aiming to achieve this new objective.

The International Quiet Ocean Experiment (IQOE) provides a framework for a decade-long project of research, observations, and modeling, aimed at improving our understanding of generation, propagation, and reception of sound in the ocean and its effects on marine organisms. The project will include carefully designed observations exploiting situations of varying sound inputs in conjunction with detailed model analysis. The project will build toward a period of intensive study of sound in the ocean, an International Year of the Quiet Ocean (see Chapter 7).

## 2.2 Rationale for an IQOE

### *Benefits of an international program*

A question often asked when planning international research projects regards the benefit of an international approach, instead of individual scientists and groups of scientists proceeding independently. There are many potential benefits of the IQOE:

1. IQOE will serve as a focal point to bring together a larger number of scientists and engineers to identify priority questions and promising approaches to answering the questions.
2. IQOE will provide a mechanism to bring together a critical mass of resources (expertise, equipment, finances) over an extended period to make progress on difficult observational, modeling, and research challenges.
3. IQOE will provide the necessity and resources for international standardization and intercalibrations for better comparison of the results of observations, modeling, and research worldwide.
4. IQOE will demonstrate the importance of ocean acoustics and biological effects to the public, managers, and policymakers.
5. IQOE will attract financial resources and staffing to provide critical infrastructural support for meeting planning, communication, development of scientific publications, and capacity building.

### *Scientific rationale*

Does the sound made by humans harm marine life and, if so, how does it interact with other stresses resulting from human activities? At present, we can offer only preliminary answers to these important questions, and only for a few species. We know that as the ocean has become more industrialized, the sound levels associated with human activities have increased (NRC, 2003; Frisk, 2012). For example, in areas where measurements have been made (mainly off the west coast of North America), in the last three decades of the 20th century, anthropogenic sound in the ocean increased in the frequency range between 10 Hz and 200 Hz (Andrew et al., 2002; McDonald et al., 2008; Chapman and Price, 2011; Andrew et al., 2011) (Figure 2.3). However, given the spatial and temporal complexity and variability in sound sources, the relative contribution of anthropogenic sound is not always readily distinguishable. An intriguing feature of Figure 2.3 is the apparent leveling off or decrease of sound levels between 1995 and 2007 in this location. Research is needed to understand the cause of the decrease in this region, and to predict whether sound levels will begin increasing again.

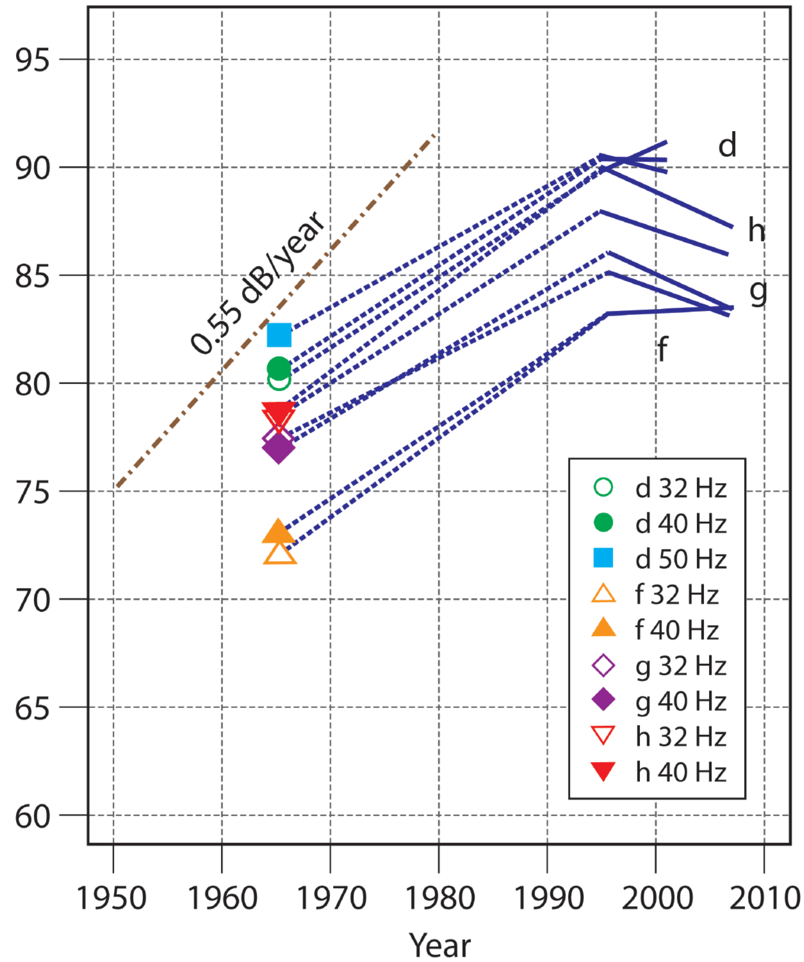



**Figure 2.3.** *Historical and contemporary shipping traffic sound levels along the west coast of North America from Andrew et al. (2011). Solid lines represent the trend lines fitted to the APL/UW data in Andrew et al. (2011), shown over the temporal span of the actual dataset. Thin dotted lines connect measurements for the same frequency band for each system. The heavy dashed line indicates the trend suggested by Ross (2005), which was based broadly on data from many systems in both the Atlantic and Pacific oceans, and not specifically on data from the systems used in Andrew et al. (2011). Reprinted with permission from R.K. Andrew, B.M. Howe, and J.A. Mercer. Copyright 2011, Acoustical Society of America.*

New sources of anthropogenic sound are being created. These include increasingly sophisticated sonar systems for characterizing the seabed, understanding the water column, and searching the ocean for hostile or lost vessels. They also include acoustic systems for geolocation and acoustic tomography used to study the physical properties of the ocean over very large scales. All of these add to new ship propulsion systems and to new technologies for drilling and mining in deep water to increase the potential challenges to marine life. Increasing our basic knowledge of the sensitivity of marine organisms to sound will allow more intelligent designs of these new technologies to minimize their impact on marine organisms.

The effect of sound on marine life is a knowledge gap in marine science. The human contribution to ocean sound has become the dominant component of the sound field in some marine environments (NRC, 2003; Hildebrand, 2009). Sound can strongly affect the lives of many marine organisms either because they have hearing sensitivity across a wide frequency range or because they produce sounds themselves. There is considerable overlap between the human contribution to ocean sound and the frequencies used by specific marine organisms (Figure 2.4). Theory and observations increasingly suggest that human sound could be approaching levels at which marine life may experience chronic negative effects (Rolland et al., 2012). We know the harmful levels for a few species, but have little information for the majority of species.

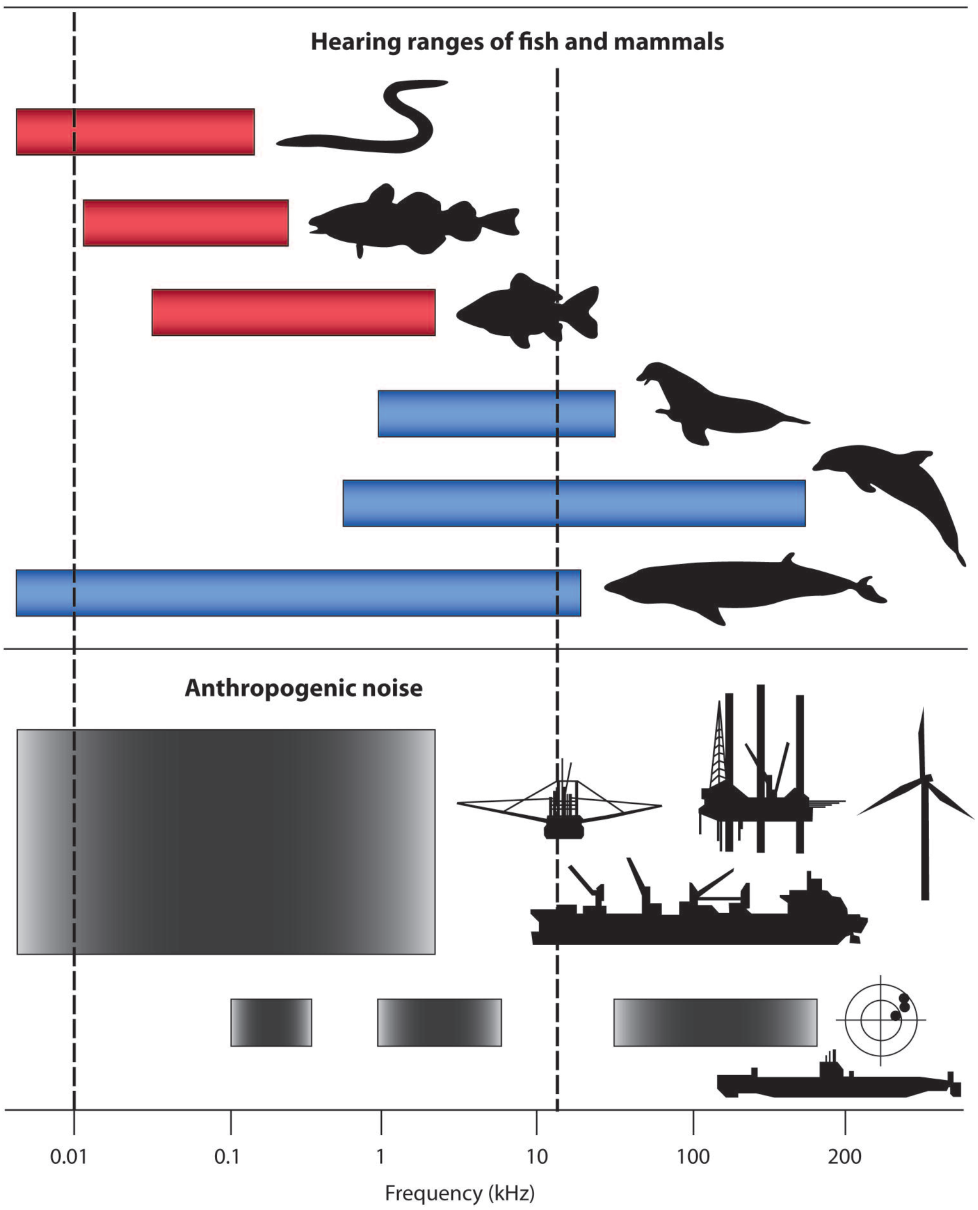



**Figure 2.4.** *Diagrammatic representation of the overlap between the hearing ranges of different kinds of fish and mammals and the frequency of sound produced by different human-generated sources (from Slabbekoorn et al., 2010). This is a considerable simplification of the Wenz curve (Wenz, 1962). The diagram does not reflect the changes in auditory sensitivity of each group of organisms, but simply represents the kind of auditory range over which sensitivity is likely to occur. Permission for reuse granted by* Trends in Ecology and Evolution.

Some marine mammals and fish show symptoms indicative of negative effects of sound, but it is currently impossible to determine whether other marine organisms are also harmed by sound because they have not yet been studied to the same extent. Although some of these effects are likely to be acute and rare in occurrence, chronic sublethal effects may be more prevalent, but are much more difficult to measure. This difficulty creates an important challenge because even if chronic effects are difficult to observe, this does not mean that they are not ecologically significant. Moreover, we need to ensure that keystone or indicator species within major, or important, ecological systems, as well as species already recognized as endangered, are not threatened by rising levels of marine sound. We need to identify the thresholds of such effects for different species and be in a position to predict how increasing anthropogenic sound will affect populations and the integrity of marine ecosystems. The IQOE is being developed with the objective of coordinating the international research community to both quantify the intensity and distribution of ocean sound, and to examine the functional relationship between sound and the viability of key marine organisms and ecosystems. This has implications for the future exploitation and management of the marine environment and will inform global, regional, and local decision-making about the exploitation of marine resources.

## 2.3 Background

The potential impact of anthropogenic sound on marine life is a matter of societal concern. Most people are unaware of ocean sound, yet it is a vital part of the ocean environment, important not only to large marine mammals, but also to fish and other animal groups. Environmental nongovernmental organizations are more aware of the issue and can motivate action of various kinds, such as industrial guidelines, litigation, and possible regulation designed to reduce the impact of sound on marine life. Such action can be expensive and must therefore be based on robust scientific evidence. Moreover, the results of such understanding need to be effectively communicated to the public to foster rational discussion, informed policy development at national and international levels, and public support for meaningful and justifiable action.

The basic scientific foundations for management of sound in the ocean fall into two related categories. First, the contemporary ocean sound field should be described adequately. This description cannot be represented by a single number, but must rather be a quantitative description of the kinds of sound that exist, and their frequencies, intensities, and variations in both space and time. An important example of the value of long time series observations of key environmental parameters is the ”Keeling Curve” that documents the changes in atmospheric $CO_2$ concentration (Keeling, 1960). Documenting changes in the ocean sound environment is more complex and will require long-term measurement with appropriate hydrophone stations across many regions, together with analysis that identifies trends in different contributions. Technological advancements allow such measurements to span a broad frequency range and to record or transmit the data in various forms. Existing systems such as hydrophones used for Comprehensive Test Ban Treaty Organization verification and various cabled ocean observatories designed principally for other functions could also provide the backbone of ocean observation for sound. Quantitative predictions of the underwater sound field will require better understanding of the different sound sources—both natural and anthropogenic—and the propagation characteristics within the ocean that contribute to the building of a “soundscape.”[3]. This will require development of numerical models of ocean sound fields based on knowledge and measurements of the sources and of the propagation environment, and of statistical models that can be used to fit the numerical models to data obtained from calibrated acoustic measurements. This validation of numerical models through testing their predictions against observations is an important part of the IQOE. Once validated, the numerical models can be used to explore the relative significance of different sources, guide design of further measurements, and provide valuable tools for planning mitigation efforts where these are found necessary.

In addition to a basic characterization of ocean soundscapes, the biological impact of the sound must be studied to guide appropriate management of sound in the ocean. For a particular region this will include knowledge of the species that occur and their sensitivity to acoustic interference. Given the generally limited state of our knowledge of biological sensitivity to sound, this represents, by far, the most challenging aspect of the scientific and management problem. We are unlikely to resolve this challenge quickly or completely. Nevertheless, a good understanding of the effects of anthropogenic sound on marine life remains essential to rational decision-making and is a central goal of the IQOE. The long range at which sound spreads in the ocean emphasizes the need for study at large scales. In addition, human activities are adding noise throughout the global ocean. The IQOE is the first project to address questions and attempt to provide answers over hitherto unexplored scales. This ambition governs the international global scale of the IQOE and its proposed duration of at least a decade.

Humans introduce sound to the ocean through many different activities. Each source may have different effects, depending on the range of frequencies produced; the source’s power output; whether the source radiates an intermittent, pulsed, or a continuous sound; and the degree to which the sound is radiated in certain directions (few sound sources are truly omnidirectional). Some anthropogenic sources—such as some military sonar, seismic air guns, pile driving, and explosions—are both impulsive and of high intensity. Götz and Janik (2011) showed that the rapid rise time of some high-intensity impulse sounds can elicit a reflex startle response that, because it is aversive, can result in sensitization to sound.

[3] *A soundscape is a detailed and comprehensive description of an* acoustic environment.

There is increasing evidence that these types of sounds can elicit strong negative reactions, or even physical injury, in some marine species. Concern about the possibility that sounds may lead to negative behavioral reactions or physical injury has led to higher levels of scrutiny for many of those sources. Recently, military sonars have been a particular focus of attention because of their association with atypical mass strandings of beaked whales (Cox et al., 2006). Nevertheless, sonar exercises occur in some areas of beaked whale presence with no recorded mass strandings (D'Amico et al., 2009). The acute effects of sonars on beaked whales probably depend on the context of the exposure (i.e., distance from sonar to whale, bathymetry, presence of surface temperature ducts, behavior, and number of naval vessels). Animal strandings are probably the most easily observed and extreme end point of a syndrome of behavioral responses to sound in these species (Boyd et al., 2007). There is increasing evidence that a similar syndrome of reduced capacity to perform normal life functions is present across a wide range of marine fauna, including fish (Slabbekoorn et al., 2010; Simpson et al., 2014) and marine mammals (Southall et al., 2007; Tyack, 2008).

Humans also influence ocean sound in an indirect way, through anthropogenic changes in the concentration of carbon dioxide and the temperature of the ocean. It has been suggested (Hester et al., 2008; Brewer and Hester, 2009; Ilyina et al., 2009) that increasing ocean acidity might increase low-frequency sound levels by increasing the ocean's transparency to sound, although theory suggests that this effect has been negligible to date (Joseph and Chiu, 2010; Udovydchenkov et al., 2010). Another possible issue is a decrease in sound due to increase in the average sea surface temperature (Ainslie, 2012). Research is needed to investigate whether this effect might explain the leveling off seen in Figure 2.3 in the reception of ship sound.

A major question in almost all of these cases is whether the impact on the fitness of individual organisms is great enough to jeopardize the viability of their populations. One broad ecosystem-based approach would relate indices of ecosystem health, such as biodiversity (potentially using natural components of the soundscape – Sueur et al. 2008; Parks et al. 2013) to indices of noise and other stressors. This approach has the advantage of enabling a rapid and very broad-scale evaluation of effects of noise on marine ecosystems. On the other hand, this approach fails to test the causal links from sound exposure through disturbance of individuals to effects on vital rates to effects on populations. A 2005 report of the U.S. National Research Council developed an approach to identify all these links (Figure 2.5), which defines a rationale for developing assessments of the significance of sublethal effects and for identifying the most important gaps in our knowledge. The greatest challenge is to define the functional relationships between behavioral and physiological responses to sound and then the biological consequences for growth, reproduction, and survival—an essential requirement of this assessment process (Figure 2.5). Defining the transfer functions between the different boxes of the Population Consequences of Acoustic Disturbance (PCAD) framework (Figures 2.5 and 2.6) and building knowledge of biological significance will be challenging. However, it may be possible to make progress through a combination of modeling transfer functions, leveraging multiple datasets derived from ongoing observational studies, passive acoustic monitoring, and the direct measurement of the level of sound received by marine organisms, usually using tags temporarily attached to those organisms or using sensors that are located near the animals.

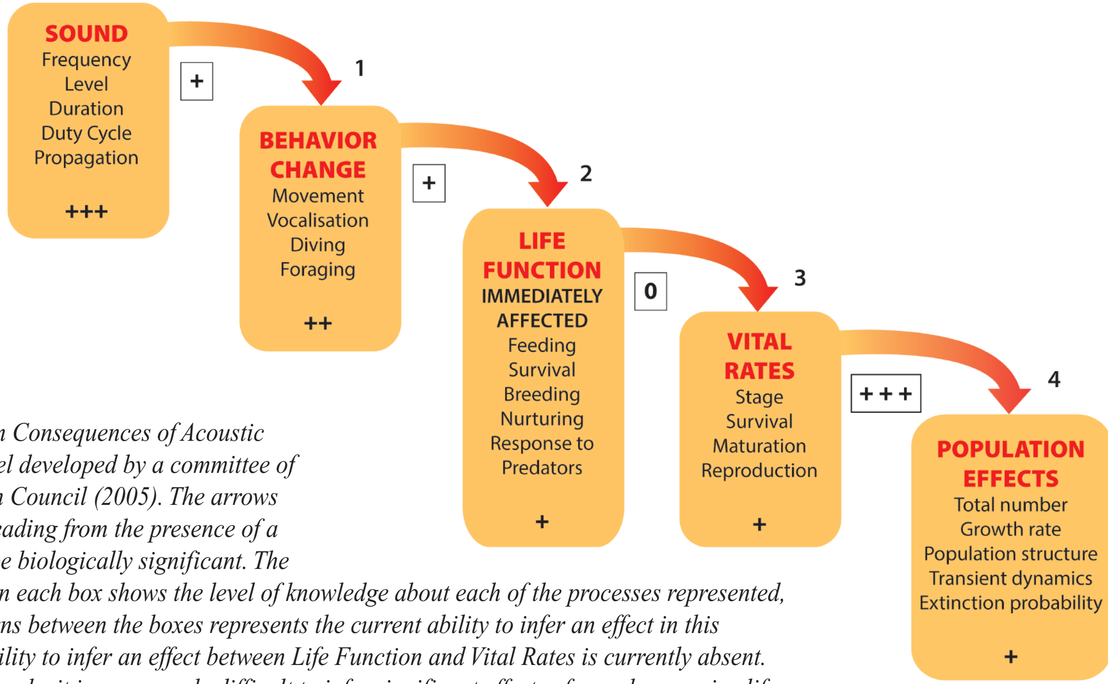



**Figure 2.5.** *The Population Consequences of Acoustic Disturbance (PCAD) model developed by a committee of the U.S. National Research Council (2005). The arrows define transfer functions leading from the presence of a sound to effects that may be biologically significant. The number of plus signs within each box shows the level of knowledge about each of the processes represented, and the number of plus signs between the boxes represents the current ability to infer an effect in this sequence. Note that the ability to infer an effect between Life Function and Vital Rates is currently absent. This diagram demonstrates why it is enormously difficult to infer significant effects of sound on marine life and also why, even if there are real effects of sound, demonstrating a connection to sound as the cause is also enormously difficult. Reprinted with permission from the National Academies Press, Copyright 2005, National Academy of Sciences.*

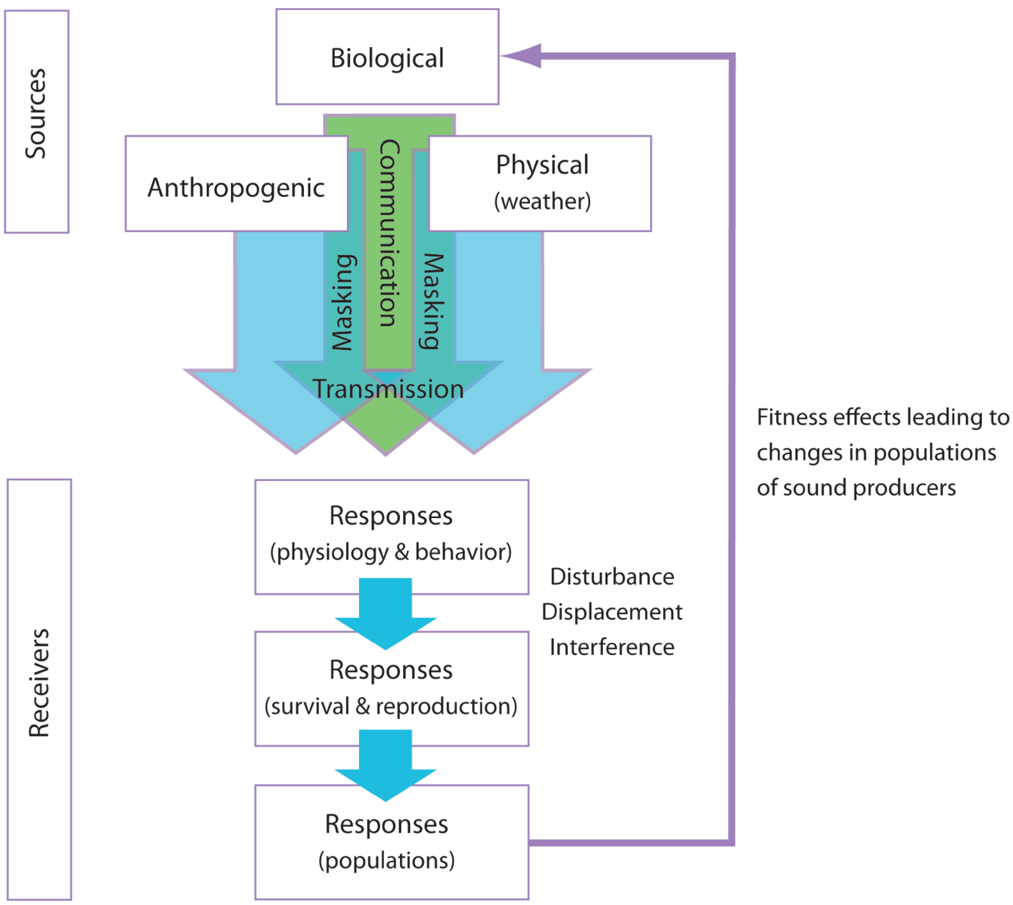



**Figure 2.6.** *A diagrammatic view of the issues being investigated by the IQOE (from Boyd et al., 2011). Permission for reuse granted by* Oceanography *magazine.*

Figure 2.6 defines three major sources of sound in the ocean: physical, biological, and anthropogenic. Physical sound sources include geophysical sources as well as sounds generated by ocean weather due mainly to wind and waves. Physical and biological sound sources can "mask" the sounds involved in marine animal communication and echolocation. Animals that rely on sound are likely to have evolved mechanisms to cope with this type of masking (Tyack, 2008). However, overlaid on this soundscape is new sound added by humans, and marine animals may not be able to handle the additional masking to the same extent. The characteristics of the sound received by organisms ("receivers") will determine responses that could cascade through physiological or behavioral effects on an animal's ability to feed, migrate, and breed and which, in turn, may lead to changes in reproduction and survival of the individual. The physiology and behavior of individuals are affected by changes in sound levels. If enough individuals are affected, the distribution, abundance, and dynamics of populations can be affected. Some fish and invertebrates rely on acoustic cues to find suitable habitat and to make the decision to switch from their larval planktonic form to settle on a substrate (Simpson et al., 2005; Montgomery et al., 2006). If noise interferes with settlement, this could have broader ecosystem effects.

Shipping has long been recognized as an important anthropogenic sound source (Wenz, 1962). The volume of cargo transported by sea has been doubling approximately every 20 years (http://www.marisec.org/shippingfacts/worldtrade/volume-world-trade-sea.php), resulting in an increase in anthropogenic sound from this source. Although the measurement of sound in relation to these changes has been mostly local and is incomplete, the current estimate is that increased shipping has been accompanied by an increase in anthropogenic sound at frequencies below 500 Hz. From 1950 to 2000, the shipping contribution to ambient sound of some locations increased by as much as 15 dB, corresponding to an average rate of increase of approximately 3 dB per decade (Andrew et al., 2002, 2011; Hildebrand, 2009; Chapman and Price, 2011; Frisk, 2012). We also know that offshore oil and gas exploration and production, as well as renewable energy developments, have expanded during the same period, as has the fishing industry.

These changes could be important to the many marine organisms that use sound either passively to listen and orient relative to their surroundings, or actively by producing sound themselves to search for prey or other objects, communicate, or in some cases as a by-product of other activities. The active production of sound is relatively easy to detect, but passive use of sound is not. It is likely that most multicellular marine organisms use sound passively as a way of sensing their environment, including listening for prey and predators, and changing behavior in relation to weather and obstacles (including moving ships or stationary human-made objects). The idea that animals may use something analogous to "acoustic daylight" (Buckingham et al., 1992) to gain an image of their surroundings is gaining momentum, even if it is difficult to demonstrate empirically. The properties of sound in water and the low levels of light penetration below the surface in many circumstances mean that sound has essentially replaced light to sense distant objects, for some species, as the principal source of environmental information (Ausubel, 2009). Indeed, sound is so important for many species that understanding the acoustic environment amounts to describing their acoustic ecology.

Setting and defining a standard for soundscape quantification will be one of the first priorities addressed by the IQOE, to facilitate an internationally coordinated scientific effort. Several years ago the International Organization for Standardization/Technical Committee 43/Subcommittee 3 (ISO/TC 43/SC 3) on Underwater Acoustics was formed to establish standards in the field of underwater acoustics, including natural, biological, and anthropogenic sound. This international group is addressing topics that include measurement and assessment techniques associated with the generation, propagation, and reception of sound, as well as its reflection and scattering by the seabed, sea surface, and organisms. Soundscape quantification and the effects of underwater sound on the ocean environment, humans, and aquatic life are also being considered. The ISO and the IQOE will coordinate activities in this area and the IQOE will develop any additional standards needed to make measurements comparable worldwide. The IQOE will hold a workshop on standardization of observations early in the project.

## 2.4 Defining the questions

Much evidence indicates that sound in the frequencies below 10 kHz is most important for marine organisms, except in the case of some invertebrates (e.g., snapping shrimp, Alpheidae species) and some marine mammals (dolphins, some whales, and seals) that have developed the capacity to both produce and, in some cases, hear complex sounds at much higher frequencies (up to >120 kHz in smaller cetaceans). Our basic knowledge of the way in which marine organisms sense sound and then respond behaviorally to different sound stimuli is rudimentary for most species and groups. Similarly, the extent to which higher background sound levels mask the ability of marine animals to interpret sound signals from their environment is largely unknown, as is the extent to which they are disturbed by loud human-produced sounds in their vicinity.

For example, we now know that several species of whales have adjusted their communication calls in a manner that suggests they are "raising their voices" or otherwise changing their calls to be heard in the context of potentially masking sounds (e.g., Au et al., 1985; Miller et al., 2000; Foote et al., 2004; Holt et al., 2008; Parks et al., 2010). This pattern of speaking louder in noise is known as the Lombard effect (Lombard, 1911), originally reported for humans, but also seen in terrestrial species such as birds that use sound in social activities (Lengagne, 2008; Slabbekoorn and Bouton, 2008). In the presence of high levels of background sound, some species simply stop vocalizing, either because they are being disturbed or because, like humans trying to talk in the presence of loud background sound, they give up because communication becomes ineffective. Acoustic masking of marine mammals from increased low-frequency ambient sound is of particular concern in species that rely on low-frequency sound, such as the large baleen whales (Clark et al., 2009), because low-frequency sound travels greater distances. Although it is possible that whales could be especially sensitive (and we know that not all whale species share the same sensitivities), the presence of masking and the Lombard effect leads to two questions: (1) how widespread are these effects among marine organisms, and (2) even if they are widespread, are they important to the function and survival of viable populations?

New research and observations also need to study biological and sensory mechanisms for increasing the detectability of signals, including waiting to call until noise decreases, increasing the rate of calling, increasing signal intensity, increasing the signal duration, shifting the frequency of a signal outside of the noise band, and the potential (energetic or fitness) costs associated with these adaptations (see Tyack, 2008 for review).

**Based on the foregoing rationale, the IQOE will address the following fundamental questions:**

1. How have human activities affected the global ocean soundscape compared with natural changes over geologic time?
2. What are the current levels and distribution of anthropogenic sound in the ocean?
3. What are the trends in anthropogenic sound levels across the global ocean?
4. What are the current effects of anthropogenic sound on important marine animal populations?
5. What are the potential future effects of sound on marine life?

## 2.5 IQOE objectives

The IQOE will last for 10 years, to provide sufficient time to ramp up the large international research effort required, for planning observations and experiments; designing and deploying acoustic sensors; developing the community of scientists and technicians necessary to carry out the planned work; and analyzing, synthesizing, and disseminating the data and information developed by the study. In broad terms, the IQOE will assess global sound characteristics in the ocean, determine whether there are trends in sound characteristics, and test the hypothesis that changes in sound characteristics affect marine habitats and species in ways that cause significant changes in their populations.

The IQOE will build a global scientific community with expertise across a broad range of disciplines and with the technologies and tools, including databases, necessary to support research in ocean sound as a core activity within future ocean science. The fundamental questions will be addressed through the organization of four research themes:

***Theme 1: Ocean Soundscapes***

- Characterizing soundscapes
- Identifying sound sources
- Modeling soundscapes
- Identifying trends in ocean sound levels
- Quantifying sound budgets
- Documenting soundscape diversity

***Theme 2: Effects of Sound on Marine Organisms***

- Identifying model species and habitats
- Employing experimental approaches, as well as comparative and baseline studies, and large-scale experiments
- Measuring effects
- Determining dose–response relationships
- Determining biological significance

***Theme 3: Observations of Sound in the Ocean***

- Establishing data standards
- Deploying new global and regional observing systems, including biological observations
- Integrating observing systems
- Conducting synthesis and modeling

***Theme 4: Industry and Regulation***

- Informing noise monitoring and regulation
- Defining thresholds
- Considering risk management
- Measuring compliance
- Communicating results

## 2.6 Anticipated benefits

The questions addressed by the IQOE are important for two main reasons. First, industrialization of the ocean is likely to increase in the next few decades. A large proportion of the manufactured goods and raw materials needed by a growing global economy are being shipped around the globe on the ocean. The demand for hydrocarbons is also pushing exploration and production farther offshore into deep waters at continental shelf edges, at depths from which sound can more easily enter the SOFAR channel. Energy extraction from the ocean wind, waves, and tides—although resulting in a relatively small amount of energy production at present—is expected to increase rapidly over the next few decades. In coastal areas, recreation is also leading to increasing sound levels from pleasure boats and cruise vessels. There are serious concerns that this process of increasing industrialization and recreation will lead us in small steps toward an intolerable acoustic environment for many marine organisms.

It is in the best interests of sound producers to help study the effects of sound on marine organisms, because the *precautionary principle* is slowly but progressively constraining the ability of sound producers to operate (Gillespie, 2007). Precaution in the face of uncertainty is rational and is an approach that is now deeply embedded in the way that environmental management operates in many countries, both nationally and through international agreements. Reducing uncertainty by increasing our knowledge and understanding of the effects of human-generated sound on marine organisms will help protect wildlife while avoiding excessive regulation.

A second and even more profound reason for giving attention to the issue of sound in the ocean is that industrialization of the ocean inevitably leads to negative effects that could perhaps be minimized with advanced planning. Humankind is slow to learn lessons from the negative impacts of the past industrialization of the ocean. The dangers of causing irreversible declines in the quality of the planet's self-regulating environment are tangible and real. The nonlinear, complex nature of the Earth system means that, although many parts of this system are self-regulating within broad boundaries, collapses could happen quickly and without much warning. At some point, small changes could lead to very large shifts in the state of ocean ecosystems. Although there is some evidence that many parts of the ocean show remarkable resilience to the direct exploitation of fish, whales, plankton, and other forms of biological productivity, there is increasing evidence that there are definite limits.

*Ecological collapse* is an emotive and poorly defined term. However, if viewed from a human perspective, as describing ecosystems that can no longer support normal goods and services, collapse has already happened locally as a result of direct exploitation (Bakun and Weeks, 2006; Thurstan and Roberts, 2010). The danger is that the uncontrolled increase of sound in the ocean—some of which could be avoided with appropriate design, planning, and technological innovation—could add significant stress to already-stressed oceanic ecosystems. Unless we improve our knowledge of the consequences of sound pollution, we may be cruising blindly toward consequences that could cost us much more than we will ever gain from ignoring them.

Therefore, the benefits of IQOE activities will accrue across many stakeholder groups:

- *Regulators* who codify emerging legal frameworks as constraints on the sound radiated by industrial activity.
- *Legislators* who design legal frameworks to regulate sound in the ocean.
- *Members of the public* who have an increasingly jaundiced view of the activities and motivation of industry, especially in the ocean, where experience of poor management in fisheries has sensitized the public to issues of marine management.
- *Managers* who need relatively simple and defensible targets and reference points to establish as objectives for managing anthropogenic sound in the ocean.
- *Scientists* because sound is usually overlooked as part of the physical structure of the ocean, and it is likely to have much more widespread importance than is currently appreciated.
- *Militaries* for which the ocean is both a barrier that aids national and international security and a challenge because it can provide cover for those with aggressive intentions. The importance of sound in the ocean has been appreciated by submariners, and those who wish to monitor submarine activity, for many decades, and much of our current knowledge of ocean acoustics derives from studies conducted to support defense and submarine warfare. We need to broaden the foundation for our knowledge of sound in the ocean.
- *Industries* that produce sound and technologists who are seeking ways to reduce the inputs of sound from commercial activities.

## 2.7 Activities

### *Experimental approaches*

To address the challenging scale of questions posed by the effects of increasing ocean sound levels we need to ensure that science activities are coordinated across international boundaries and across disciplines. This is why the IQOE has been proposed. The IQOE will employ two approaches to help increase our understanding of sound in the ocean and its effects. One of these approaches will be to conduct experiments involving the active manipulation of anthropogenic sound sources, either through directed, temporary reductions of these sound sources at regional scales, or through planned lulls in sound production (e.g., due to planned shutdown of offshore construction, the diversion of shipping lanes, or the temporary presence and absence of sound sources). The second method will be to make opportunistic observations of the effects of anthropogenic sounds on marine ecosystems and species. These experimental approaches will require expanded observations and modeling.

### *Ocean soundscapes*

A first step in this direction will be to define what we call *ocean soundscapes*. An ocean soundscape is a characterization of the acoustic environment that fully describes its spatial, temporal, and spectral characteristics. Although we have identified at least 30 sites or networks globally that have currently or recently collected data about ocean sound (see Appendix II), in almost all cases the monitoring stations involved have been established to perform specific functions. This is reflected in the disparity of sensor designs and of data collection and transmission protocols. We need to find ways to use these data in a unified framework and to establish other measurement systems to understand the complex global sound field in the ocean. Building a picture of this global sound field, even in a relatively unrefined form, is a high priority as a baseline for other studies. Sound propagation modeling—based on ship position and activity (from Automatic Identification System data, e.g., Hatch et al., 2008), data for wind and rainfall, and data for seismic surveying, sonars, pile driving, and explosions—may provide a general view of the sound fields across the global ocean.[4] The most challenging "unknown" in estimating the global soundscape will probably be the contribution of biological sound, which will require better understanding of animal vocal behavior, particularly when species vocalize in large numbers to produce "choruses." Refinement of the quantification of sound fields will be possible with increasing knowledge of the sound production from ships and other human activities, many of which are currently poorly characterized.

The IQOE will promote the establishment of a network of stations making acoustical observations. This network will build on the existing and planned capability of the Global Ocean Observing System (GOOS) and on local and regional systems such as the U.S. Integrated Ocean Observing System and the Australian Integrated Marine Observing System, by helping to define standards and protocols for sensors and for the analysis, storage, and distribution of data across a global research community. Some elements of global ocean observation systems actively produce anthropogenic sounds that can be used for acoustic tomography or for global security, but the IQOE will focus on passive acoustic systems rather than active acoustics. This means that it is not envisaged that the IQOE will promote the use of active systems, such as Doppler profilers, swath bathymetry, tomography or seismic arrays unless they are a specific part of an experiment to understand their effects on marine life or are necessary for in situ acoustic calibrations.

> The IQOE will not introduce sound to the ocean at durations or levels that will produce long-range effects. Any introduction of sound will either be at high frequencies or at low enough sound levels and durations that the IQOE will not significantly add to global ocean noise pollution. An important aspect of the IQOE will be determination of the hearing capabilities of marine organisms and dose–response relationships, which will require limited and controlled addition of sound to the ocean. Such additions will be subject to normal permitting and animal care requirements. The IQOE will also take advantage of the noise-producing activities of industry and navies, where possible, to study the impacts of such noises on marine organisms.

### *Predicting sound fields and managing sound inventories*

Characterizing the global ocean soundscape, with appropriate estimation of statistical uncertainty around variation in space, time, and frequency, is a necessary step toward predicting ocean sound fields in particular locations. These predictions can then be compared with in

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[4] *The IQOE will explore with navies and exploration firms how to obtain useful information from their activities without compromising the security and proprietary aspects of their data.*

situ measurements from existing sites, and a process of tuning sound field models to maximize the fit to the empirical observations will eventually refine the descriptions of ocean soundscapes. This global analysis of ocean soundscapes may enable classification of soundscapes into types that may facilitate grouping experiments or data according to the sound environment in which they were conducted. The goal of the IQOE is to maintain a global long-term focus, which will inform local efforts in modeling and measuring both sound fields and effects of sound on marine organisms and ecosystems.

Predicting sound fields in this way will also feed directly into the emerging processes for the regulation of offshore human activities and general industrial development. In both the United States and Europe, for example, legislation is moving rapidly to embrace marine spatial planning and setting standards for sound exposure, principally on a precautionary basis. But existing information is not sufficient to build the rationale for spatial management of industrial activities to reduce potential sound impacts on sensitive species or habitats. Marine spatial planning faces particular problems for pollutants such as sound that can spread hundreds or thousands of kilometers, covering the global ocean (Hatch and Fristrup, 2009). The development of sound budgets[5] on the global scale will enable regional and local managers to refine these budgets to reflect their own needs at regional and local scales, and to help define the kinds of threshold values that managers often need in order to set legally binding conditions on use of the ocean. This spatially nested approach to model development and validation is necessary because characterization of sound in the ocean needs to be tackled initially at large scales given the long-range propagation of low-frequency sound. Even local models need to have specified boundary conditions to build local sound budgets and we intend to provide this capability.

#### *Preindustrial sound levels*

What was the soundscape of the global ocean like before large-scale industrial activities in the ocean? Many have explored this question with respect to the removal of marine mammals and fish, in particular, but we also want to know how noisy the ocean was in the past. In other words, can we back-cast the ocean soundscape to a preindustrial era? Given estimates that current baleen whale populations are only a small portion of pre-whaling levels, it is likely that the ocean had a much higher level of biological noise in the preindustrial era, particularly in the low frequencies.

Similarly, can we predict the ocean soundscape in the future if current trends continue? Given historical changes in sound levels, what is the cost-benefit trade-off if regulations are set to reduce the sound produced by human activities? These questions, though interesting in their own right, have most relevance if they are accompanied by robust functional relationships between sound and the growth or decline of populations of marine organisms.

### 2.8 Summary

The development of a body of knowledge that begins to flesh out the types of responses of individual organisms to different levels of sound—responses such as changes in the reproductive rate, growth rate, use of habitat, survival rate and benefits from the social structure—is an essential part of the strategy being adopted by the IQOE. The species that need to be included vary across the full range of marine organisms, but perhaps could focus principally on some of the keystone or indicator species within major, or important, ecological systems, as well as species already recognized as endangered. Many of the resulting "effects" studies will be small-scale in situ experiments, and some may be possible in controlled conditions in the laboratory. However, all experiments must be designed carefully with controls and also with a view to ensuring that the effects observed can be built into larger-scale strategic models of effects at population and ecological levels.

The challenge and opportunity of the IQOE is to coordinate scientific activities concerning the effects of ocean sound on marine organisms internationally, whether conducted in the academic, governmental, or industrial (e.g., Joint Industry Program) sectors. The framework set out in this document is intended to provide the template that will meet this challenge for the benefit of human society and the environment.

[5] *Sound budgets are defined as the overall distribution of sound energy at a particular location within a defined period of time. A budget may break down the total received sound level by source, but since not all sources will be known, this is not a prerequisite for the construction of a budget.*

# Chapter 3
# Theme 1: Ocean Soundscapes

## 3.1 Characterization of soundscapes

Quantitative description of the ocean sound field, which is how we define soundscapes, is fundamental to any analysis of trends in the levels of sound in the ocean and the effects of these trends. If we wish to understand the consequences of variation in sound within the ocean, it is essential to define variation in the sound field, spatially, temporally, and with respect to frequencies. The term soundscape used in the context of the ocean has resonance with a landscape. While light is the principal source of environmental information about a landscape for many terrestrial animals, water-dwelling animals rely to a much greater extent on sound, especially below the upper sunlit ocean layer. Use of the term *soundscape* reminds us of the central role of sound in providing cues to aquatic animals about their surroundings.

The term *soundscape* has developed recently within the terrestrial environment (Pijanowski et al., 2011) and has also been applied in a marine context (e.g., Cotter, 2008). A soundscape is a description of an *acoustic environment*. However, while an acoustic environment can be perceived from the various perspectives of receivers of signals, we follow Pijanowski and colleagues' (2011) definition of soundscape as a quantification of the ocean sound field and how it varies in a way that is unbiased by the method of measurement. This view recognizes that the acoustic environment of two colocated organisms (or receivers) that have different capacities for sound perception could be very different, but both are in identical soundscapes. We must take care to distinguish between soundscape and the way in which an individual receiver may sense different components of the soundscape.

Variation in the soundscape is central to almost every aspect of the IQOE. The soundscape is the context within which any field experiments (Theme 2) have to operate by observing the response of organisms to intentional or uncontrolled changes in it. It may also be used to document the contribution made to ocean sound by humans and as a measure of the extent of industrialization of the ocean.

At any time within a defined space, a soundscape may be described quantitatively in terms of different measures, such as

- the acoustic waveform as a function of time;
- the spectrum (sound intensity versus frequency over appropriate time scales; for example, narrow-band spectrum, 1/3-octave band levels);
- the spectrogram (time history of spectra); and
- sound energy over specified time scales, often referred to as sound pressure level (particularly to describe high-level transients).

Figure 3.1 illustrates a cross section through a soundscape (also illustrated in Figure 2.1), where a broad-band acoustic spectrum has been measured across time, in this case for three weeks, to form a spectrogram displaying acoustic energy as a function of frequency versus time. Presented in this form, which is the normal form for the depiction of the dynamics of ocean sound measured from a particular observation station, the soundscape can be rather difficult to interpret. It is difficult to verify independently the interpretations given in such figures, which rely on the experience of the observer. Spectrograms that use long-term spectral averaging often contain sounds for which there is no obvious source or explanation. Such displays can be useful for illustrating long time-varying datasets, but it is often difficult to ascertain the detailed structure of many signals, and short transients may not be visible at all. Use of detectors tuned for specific signals is a critical tool for fully describing these datasets.

The variation in the soundscape represented by the different sections in Figure 3.1 is remarkable. This kind of variability is what would normally be expected within ocean regions where there are a wide variety of different sound sources, including natural physical and biological sound, as well as human-generated sound. The increase in sound attenuation in the ocean as sound frequency increases means that the spatial scale reflected in a spectrogram such as that shown in Figure 3.1 changes from small scale (a few kilometers) at the top of the central diagram to a very large scale of hundreds of kilometers at the bottom of the central diagram. Soundscape analysis aims to present the distribution of acoustic energy within a defined region, with an ultimate goal of predicting the acoustic energy received at any point within the soundscape.

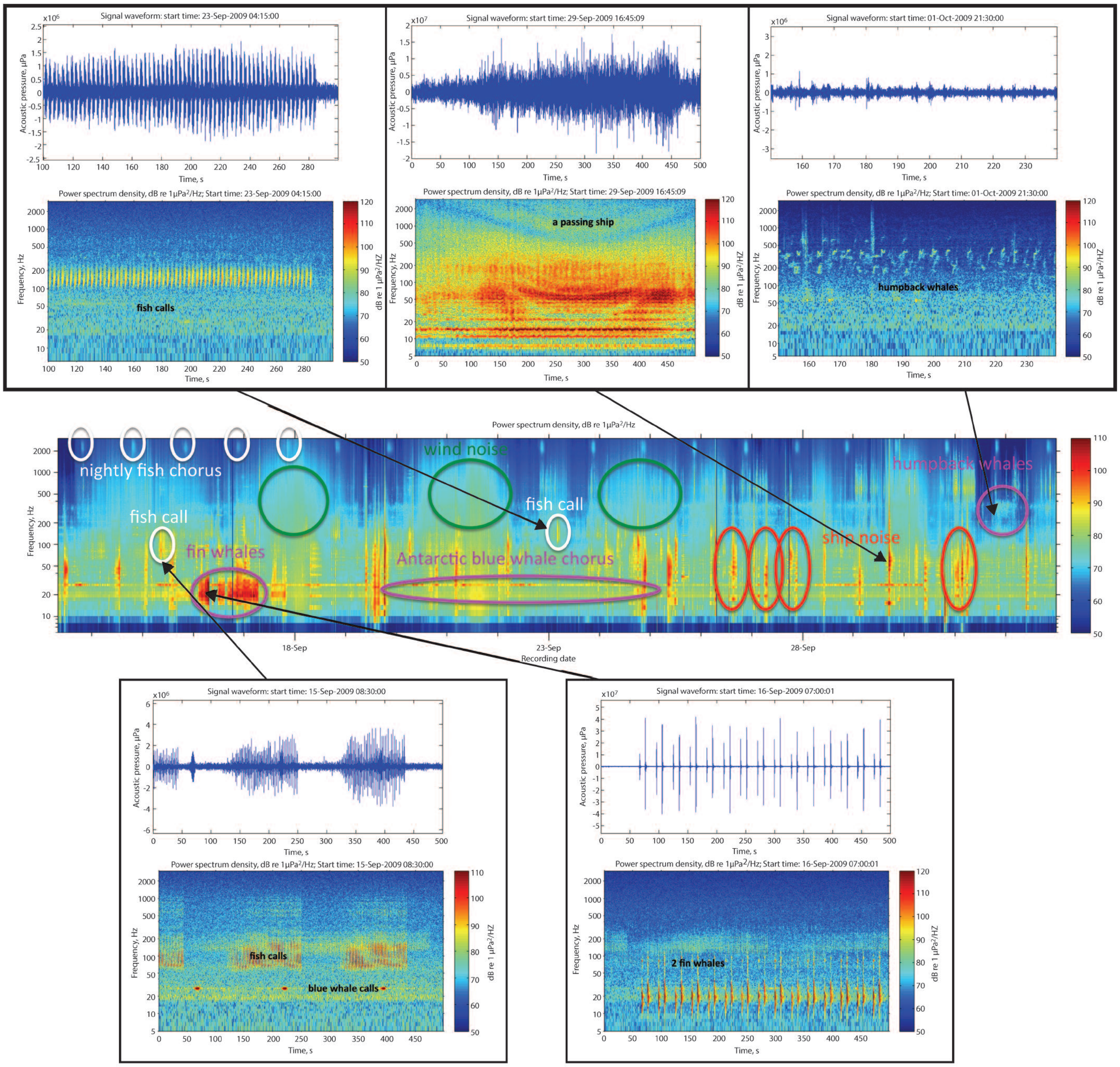


**Figure 3.1.** *The middle panel shows a 3-week spectrogram of the marine soundscape at the IMOS Perth Canyon acoustic observatory. The sounds of fish (individual fish calling and regular nighttime chorus of fish), Antarctic blue whales, fin whales and humpback whales, wind, as well as passing ships are detected and a few examples are labelled. The five panels (3 above and 2 below the 3-week spectrogram) show zoomed-in spectrograms of a few example sound signatures, and their pressure time series waveforms. Data and images courtesy of Centre for Marine Science and Technology, Curtin University, Perth, Western Australia.*

Characterization of a soundscape at a specific location first requires measurements of the received sound field over sufficient time to sample its diurnal and seasonal variation. Components of the ambient sound field may be identified (Cato, 2008) from these data, such as sound generated at the sea surface or by ships and marine organisms. These components can be related to other, more readily measured or estimated, variables such as wind speed (which is a very good predictor of sea surface sound), the distribution of ships, and the migrations and distributions of animals that produce sound. Sampling of the received sound field also can help to classify components of the soundscape that have no known source.

In addition, where a few individual sources make significant contributions to the soundscape it will be possible to model the contribution using a knowledge of source levels and directionality (sound output from the sources) and propagation loss. Examples include the contributions from passing ships and from whales. In particular, this approach will be useful for estimating the contribution of higher source level anthropogenic sounds, such as from seismic surveys and pile driving.

In some cases, it may be possible to use this modeling approach to estimate some components of the ambient soundscape. In few cases will the necessary knowledge of source levels and behavior be available for individual sources where many individuals are involved, such as in the sounds of distant shipping, but some source characteristics can be estimated through statistical approaches. For example, traffic sound may be modeled from averaged shipping densities and averaged source levels. Comparison with measurements of shipping sound would be required for validating the model and then adjusting it to maximize its fit. In other cases, such as biological choruses, so little is known about the distributions of animals that produce sound on the spatial scales required (i.e., close enough to contribute to the soundscape) or the source levels, or the sound-producing behavior, that modeling their contribution in this way has generally not been feasible. Greater success has been achieved with empirical modeling from the temporal and spatial variation of the measured biological components. In fact, this information can be coupled with information about calling rates to use sound to estimate the abundance of sound-producing animals (Marques et al., 2012).

Predictions of soundscapes can be extended to a wider range of locations by a combination of empirical modeling based on the measured characteristics and behavior of components with their relationship to readily available variables on which they depend (e.g., wind speed for sea surface sound) and modeling of the contribution of sources from their distributions, source levels and propagation loss, where this information is available.

The complete characterization of soundscapes can be achieved only to within certain bounds of accuracy. The uncertainty involved arises because of limitations in knowledge of the characteristics of the sources involved, their distributions, abundance and the spatial and temporal variation, as well as the limitations in modeling. Fundamental inaccuracies exist within sound propagation models, which are necessarily approximations of the physics involved, and there are limitations in the environmental knowledge needed in the propagation models. There are further limitations in our knowledge of marine animal distributions, their source levels and behavior. These limitations will constrain our ability to predict soundscapes based on information about individual sources and it will be important to quantify uncertainties of IQOE soundscape models. Most natural and many human sources of sound have poorly known characteristics, and radiate sound power levels that vary over multiple time scales, growing louder, then quieter, and sometimes dying away completely. This variability can be characterized using probability functions, although it is likely that the actual variability of measured sound will be accompanied by quite high levels of uncertainty.

The difficulties associated with decomposing all elements of a soundscape to known sources at known ranges are so daunting that some biologists have proposed a radically simpler way to relate soundscapes to critical ecological parameters. Sueur et al. (2008) propose an acoustic entropy index that can be calculated from recordings of environmental sound with no requirement of knowledge of each source, and they suggest that this index correlates with biodiversity in terrestrial habitats that they recorded. They also propose an acoustic dissimilarity index, calculated for pairs of recordings, which they suggest correlates with the number of acoustically active species that are not shared between terrestrial habitats. Depraetere et al. (2012) critique the acoustic entropy index for changing with varying environmental noise of nonbiological origin, and they propose a different index for biodiversity called “acoustic richness.” Parks et al. (2013) point out that noise can be an even greater problem in the marine environment, where sound propagates over longer ranges than in terrestrial environments. They analyzed acoustic data from three oceans, identifying known low-frequency calls from whale species. They then showed that noise-compensated entropy values correlate better with biological source data than with noncompensated entropies, which were strongly affected by anthropogenic noise. This radical simplification of the problem can enable first-order estimates of ecological status of habitats, but these will need to be validated over time with better biological data.

Sound levels are usually determined by measuring sound pressure levels, but many fish and invertebrates sense particle velocity representing the actual motions of fluid elements in response to the fluctuating pressure of the sound field. The particle velocity, which may be affected by turbulence, internal waves, and eddies, is a vector quantity that gives information about the proximity and direction of a sound source. As fish and many invertebrates detect particle motion, they may be especially capable of determining the direction of sources in the horizontal and vertical planes. Hence, methods of measuring or estimating particle velocity need to be included to characterize sound sources and exposures for these species.

***Key questions***

Relevant questions related to the characterization of soundscapes include the following:

- What acoustic frequencies are relevant to the ocean soundscape?
- What quantities and metrics are useful to measure components of soundscapes?
- What are the contributing components of soundscapes?
- How should the contributing components be combined to characterize and differentiate soundscapes?

***Research approach***

The current state of knowledge allows us to approximate the sound propagation from particular sources if the sound characteristics (e.g., sound level, spectrum, directionality, transmission timing, location, movement, orientation) are known. We also have significant knowledge of components of ambient sound. The most productive approach to increasing knowledge of soundscapes would be to develop a framework for calculating soundscapes from local to global scales. Ideally, this would be at all scales in three dimensions and it would also illustrate how the soundscape changes through time, but we will need to structure the approach carefully to allow for progress within the current constraints of the data.

An approach combining a series of measurements at particular locations with models will allow us to characterize soundscapes at these locations, including the way in which they change diurnally and seasonally, with the weather and with migrations and behavior of marine animals. Measurements will be delivered through Theme 3, on Observations on Sound in the Ocean.

From observations and modeling we will move toward regional, ocean-basin scale and global characterization of soundscapes. We will use a nested approach by first focusing on the global or ocean-basin scale with relatively coarse spatial grids and also on local characterizations of the soundscape where high-quality data are available in some specific places from local sensors. Models to describe sound propagation and the ocean conditions to determine sound speed are both available at the large scale. These global-scale results can be used to define the boundary conditions for calculations of the soundscape at regional and local scales, both of which require much smaller grid sizes.

The global-scale characterization will use global approximations for oceanic conditions, including seasonal variation and use of grid sizes commonly available for global oceanographic datasets. Datasets are available for the three additional layers required to describe a global soundscape, namely (1) weather as a physical sound source, using global weather and climate model outputs; (2) the distribution and density of biological sound producers within broad classes (e.g., toothed whales, baleen whales, snapping shrimp, demersal fish biomass); and (3) anthropogenic sound sources using the best available knowledge of the distribution of human activity. This approach should include the statistical uncertainty connected with those components (see Section 7, Example 1). Bottom-up approaches (i.e., small-scale studies to identify how various factors contribute to local soundscapes) might contribute to ground-truthing global model outputs. This approach may also drive the initiation of case studies in specific or characteristic soundscapes to capture information on local soundscape composition and variation for a set of representative "archetype" soundscapes.

Initial calculations of this global soundscape will include high levels of statistical uncertainty, but they will create a clearer view of where the greatest statistical uncertainties lie and also the most effective way in which this uncertainty can be reduced. Soundscape characterization is vital at an early stage of the IQOE because we need to identify those variables that lead to the greatest uncertainty. This process will lead in the remainder of the IQOE to a focus on assimilating or collecting the data that will contribute most to the reduction of statistical variance in soundscape calculations, much of which will be delivered through Theme 3 on Observations on Sound in the Ocean.

The output from this work will be a map showing the intensity of sound across the ocean. The method of representing this intensity will require more work; there are many different ways of representing sound intensity, but it is likely that the map will display the integrated total power throughout the global ocean. The integration intervals over space and time are an important research topic. The temporal integration could range from the integration time for mammalian hearing (less than 1 s) to decades, depending on the research question. Spatial integration can range from meters to thousands of kilometers and can depend on frequencies of interest. These issues of integration intervals are one aspect of standardization of measurement techniques that the IQOE will address.

Future iterations of the global soundscape characterization will include variations based on different scenarios associated with the physical, biological, and anthropogenic data layers. Three example scenarios follow:

2. Changing the biological layers to those more representative of an era before large-scale industrial fishing and whaling will allow us to test the hypothesis that the biological contribution to ocean ambient sound is considerably less now than it has been in the past.
3. Prediction of the changes on ocean ambient sound in the Arctic associated with ice retreat (including sound generated by iceberg calving and the progressive breakup of polar ice sheets) and increasing industrialization of the Arctic Ocean (see Section 7, Example 2).

*Ambient noise* is the term sometimes used to describe background sounds that merge in such a way that their individual sources cannot be distinguished. More formally, it may be defined as sound in the ocean that, in the absence of a specified signal, is received by an omnidirectional sensor and does not result from the sensor or observing system. Consequently, the level of ambient noise is a function of several factors, including the number, source levels, and bandwidth of sound sources and their range from the detector. If different sound sources overlap in frequency, the signal received will be a merged signal from all the sources producing sound in that frequency band, and it may be impossible to untangle the different sources. Figure 3.2 shows this pattern of complexity involving overlapping sound sources.

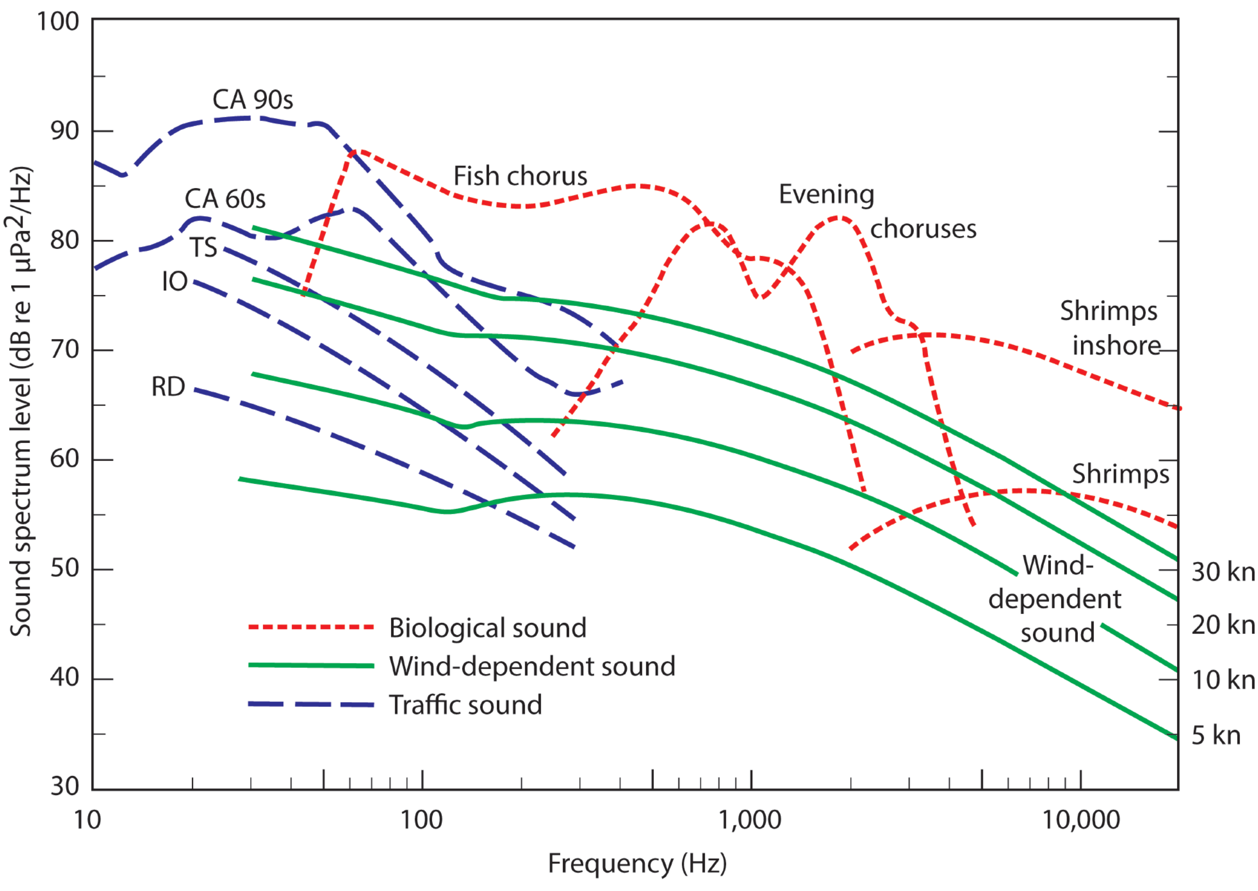


**Figure 3.2:** *Summary of ambient sound spectral density components shown as averages of sustained background sound levels. These components can be combined to predict soundscapes for particular conditions. Traffic sound is the sound of distant shipping and excludes close ships. "CA 90s" shows levels measured off California in the late 1990s (Andrew et al., 2002) at the same place and using the same methods as the curve "CA 60s" measured in the early 1960s (Wenz, 1969). Lower levels of traffic sound occur off Australia: "TS" Tasman Sea, SW Pacific, "IO" SE Indian Ocean, "RD" remote (from shipping lanes) deep water. Wind-dependent sound is from breaking waves for the wind speeds shown. The biological choruses vary with time of day and season (typical maximum levels shown). "Shrimps" refers to the sustained background sound from snapping shrimp in shallow water (modified from Cato, 1997). Permission for reuse of the figure is granted by The International Institute of Acoustics and Vibration.*

Finally, the IQOE aspires to make soundscape characterization the centerpiece of the assessment of the global trends in ambient sound. This goal is only aspirational at this stage because of the immense amount of work required before it can be achieved. For the immediate future the development of assessments of global trends in ambient sound needs to use time series of data that are, by definition, collected at single points. Since these points are relatively few in number, many have only short time series and, in most cases, it is difficult to filter out near-field transient sound sources. It will be challenging to compile an authoritative view of whether ambient sound is increasing, but soundscape characterization is one approach that can integrate data from many sources—physical, biological, human—to examine trends in sound based on a broad range of historical time series and forecasting mechanisms. Where there are individual time series of sparsely distributed observations (see Theme 3), it should then be possible to validate the resulting soundscape predictions against these observations. This approach has the potential to provide, eventually, a truly global integrated assessment of trends in ambient sound.

One imaginative approach to establishing long-term observation of trends in ocean sound would be to place an observatory in the sea below the landward end of an Antarctic ice shelf. Although technically challenging to implement, this would allow monitoring of a deep-ocean acoustic environment in the absence of near-field biological and weather sound. There would be a need to ensure that ice cracking sounds did not occur to such an extent that they were a significant influence on the capacity to measure the long-range sound field. Both the Ross and Filchner ice shelves would be appropriate for this purpose and would "look" out into the South Atlantic and South Pacific oceans, respectively.

A final added benefit of characterizing soundscapes is that it may be possible to identify areas with rare soundscapes that deserve protection. This approach has been suggested in terrestrial environments (Dumyahn and Pijanowski, 2011), but it is not known whether the same approach will be feasible in ocean environments.

## 3.2 Ambient sound and the components of soundscapes

Ocean soundscapes are composed of a combination of *ambient noise* and sounds from sources that can be localized.[6] These are often transient or pulsed sounds, or occasionally they are from sources that are completely characterized in terms of their spectrum, and their contribution to ambient sound can be inferred or calculated. However, the term *ambient noise* may sometimes be used as a surrogate for a sound field in which there are no specific identifiable sources.

Ambient noise includes sound from the sea surface, sound from distant shipping (defined as *traffic sound* by Wenz, 1962) and biological choruses when animals are so numerous that the sounds of individuals merge into a continuous background. Localized individual sound sources include passing ships, other human activity (e.g., pile driving, seismic air guns, and sonar), as well as sounds of individual animals vocalizing. Soundscapes include both natural and anthropogenic components. Figure 3.3 gives an example of the sound spectrum from pile driving. The natural components can be further subdivided into physical sound sources, such as weather or ice, and biological sources, such as snapping shrimp, fish, and whales.

Ambient noise has been studied extensively for about 70 years so that we have substantial knowledge of the characteristics of ambient noise in general, and in many environments in particular. Historically, most of the measurements of ambient noise have been motivated by strategic naval considerations. Much of the research has been in areas near North America and Europe, where the highest density of human-induced sound is observed. This leaves significant deficiencies in knowledge for areas of the world where there is less or very little human activity, although there has been some work in areas with lower densities of sound from human activities, such as Australia, New Zealand, and the Antarctic.

[6] *Note that some people refer to ambient noise as all measureable sound that is not of specific interest, irrespective of whether it can be localized.*

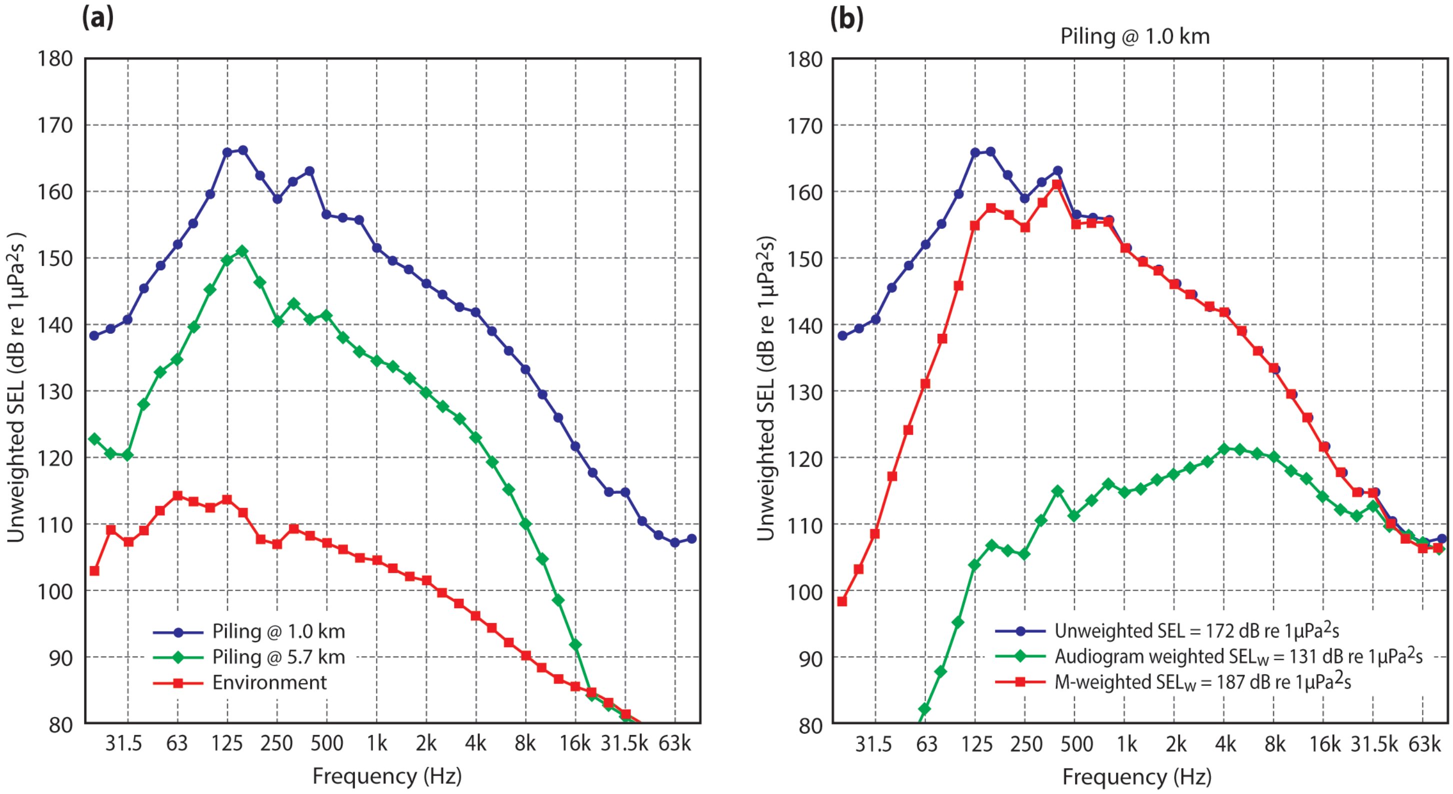


**Figure 3.3.** *(a) The average 1/3-octave band spectra of the sound exposure level (SEL) at two different distances from a piling operation, compared with the SEL of the average noise (ambient sound plus sound from measurement platform, integrated over one second duration) in the absence of the piling signal. (b) Shows the same 1/3-octave band spectra of the SEL after M-weighting the audiogram to compensate for the sensitivity of cetaceans that tend to hear best at higher frequencies. From De Jong and Ainslie (2008). Permission from the authors and from the Société Française d'Acoustique to reprint the figures.*

Sound associated with local weather conditions, especially wind, can form a substantial component of the sound field (Figure 3.2). In the absence of precipitation, wind speed can therefore be used as a proxy for the sea surface sound component of ambient sound because many studies have shown that the two are well correlated. Figure 3.4 shows results of a study carried out in the Tongue of the Ocean in the Bahamas, which is almost completely isolated from other background ocean sound and therefore provides a useful environment in which to calibrate the relationship between wind speed and ambient sound. The figure shows a consistent and linear pattern of wind speed and ambient noise level, raising the possibility that surface wind speed data can be translated into an ambient sound prediction, although this assumes similarity between the Tongue of the Ocean and other locations. Before using this type of relationship in a general sense, it would be useful to see this result replicated for other environments.

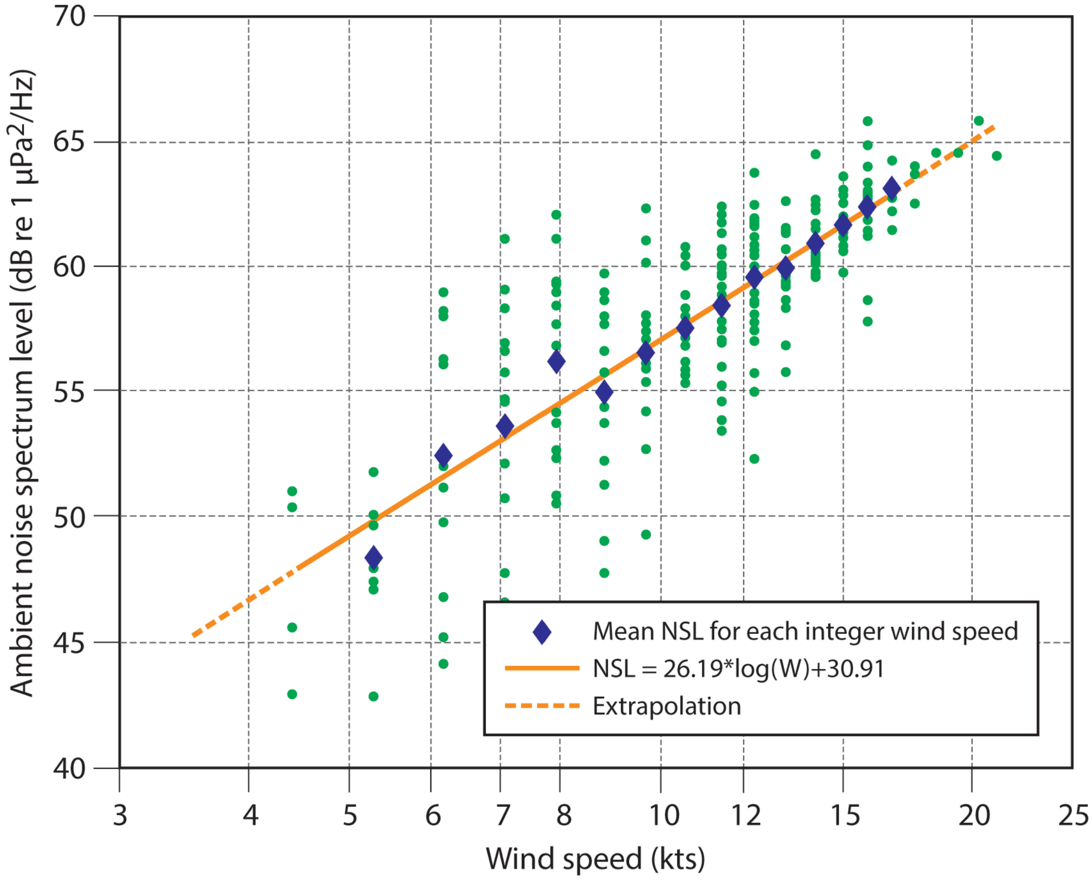


**Figure. 3.4.** *Ambient noise spectral density level (NSL) in relation to wind speed (knots) at frequency 1 kHz. Small data points depict 495 NSL values used to establish the correlation with integer values of the log of the wind speed. Diamonds depict mean values of NSL for each value of wind speed. The solid line indicates the linear regression based on mean values (diamonds). Dashed lines indicate regions of extrapolation of the regression. From Reeder et al. (2011). Used with permission from Acoustical Society of America, Copyright 2011.*

Temporal variation in ambient noise is substantial, typically around 20 dB, because of variation in weather and biological activity, with extremes of variation in excess of 30 dB. Localized individual sources can add substantially to the sound levels and variability in a soundscape. An example of the spectral and temporal variability of a soundscape off the Queensland coast is shown in Figure 3.5. Various natural and anthropogenic sources, continuous and transient, nearby and distant, contributed to this spectrum but, in general, only very specific sound sources, including two pingers, can be clearly distinguished. This type of plot showing the percentiles of variability in the amplitude of the ambient sound spectrum helps to summarize the ambient sound field.

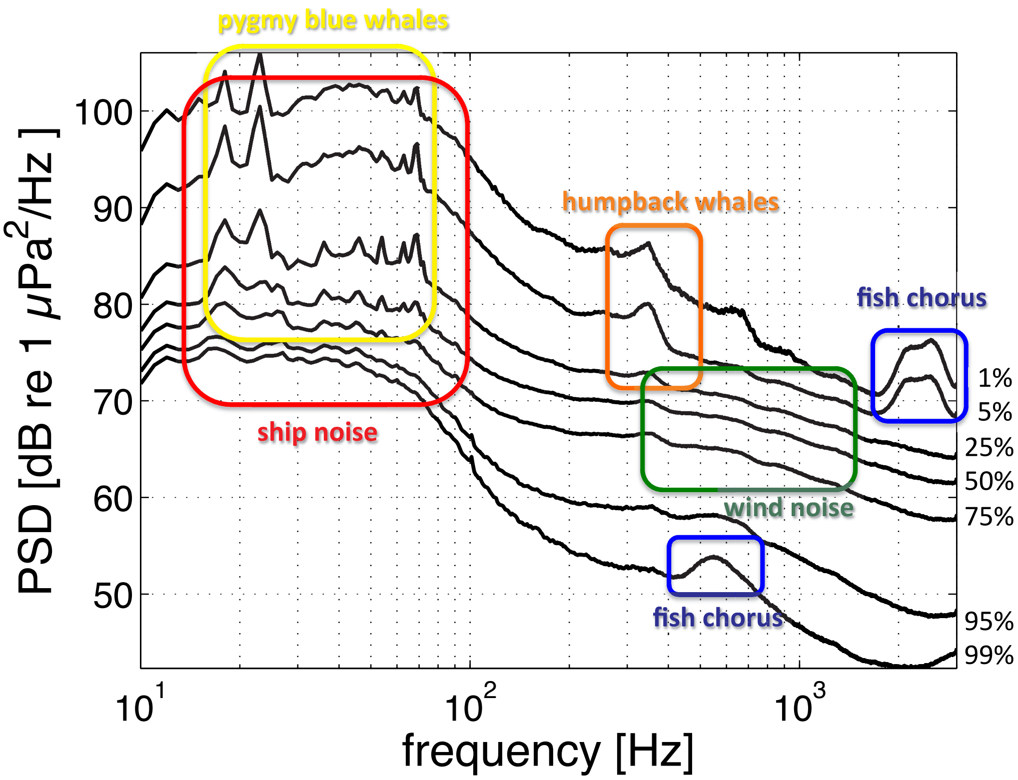


**Figure 3.5.** *Temporal variability of ambient sound spectral density (PSD) recorded over a full 12-month-period at the Integrated Marine Observing System (IMOS) acoustic recording station in the Perth Canyon off Western Australia. The nth percentile gives the level that was exceeded n% of the time. The 50th percentile is the median. Data and image from Centre for Marine Science and Technology, Curtin University, Perth, Western Australia.*

The identification, characterization, and localization of sources that contribute to a complex soundscape in a given location at a given time is a key factor in understanding soundscapes and their effects on marine life. "Source separation" can be spatial, temporal, spectral, or statistical (or a combination). It is important to appreciate the physical mobility and statistical nonstationarity of most of the sources of interest (at various scales) that often lead to using nonstationary descriptors such as spectrograms, in spite of their shortcomings.

As mentioned earlier, there are growing efforts to use environmental recordings to characterize the biodiversity of habitats, and differences between habitats. However, it is particularly important to separate nonbiological and anthropogenic sources of sound from the data used for these estimates, as this noise will bias the desired signal (Parks et al., 2013). The selection of time and location of recordings will also have to take into account temporal variation in signaling, propagation, and noise, and different ranges of propagation of sounds of different frequencies.

However, it is also important to understand why ambient sound amplitude and frequency vary through time. Sound profiles such as those illustrated in Figure 3.1 can provide clues about the sources of sound and, consequently, allow a certain amount of disentanglement of the ambient sound profile. For example, in regions where there is unlikely to be a large amount of local pleasure boat traffic, diel variation is very probably caused by biological sources that are often much more active at night than during daylight (see snapping shrimp in Figure 3.1). Diurnal variations in shipping noise have also been attributed to day-night differences in shoaling behavior of fish whose swim bladders absorb sound energy (Figure 3.6). Similarly strong seasonal trends in ambient sound in particular frequencies have been observed by the hydrophones deployed by the Comprehensive Test Ban Treaty Organization (CTBTO) in the Indian Ocean, and these are most likely associated with whale migrations. Annual changes with specific timings may also be related to weather, although there is evidence from some locations that the single most obvious signal is whale migrations on a seasonal time scale even compared with sound from wind and shipping (Burtenshaw et al., 2004).

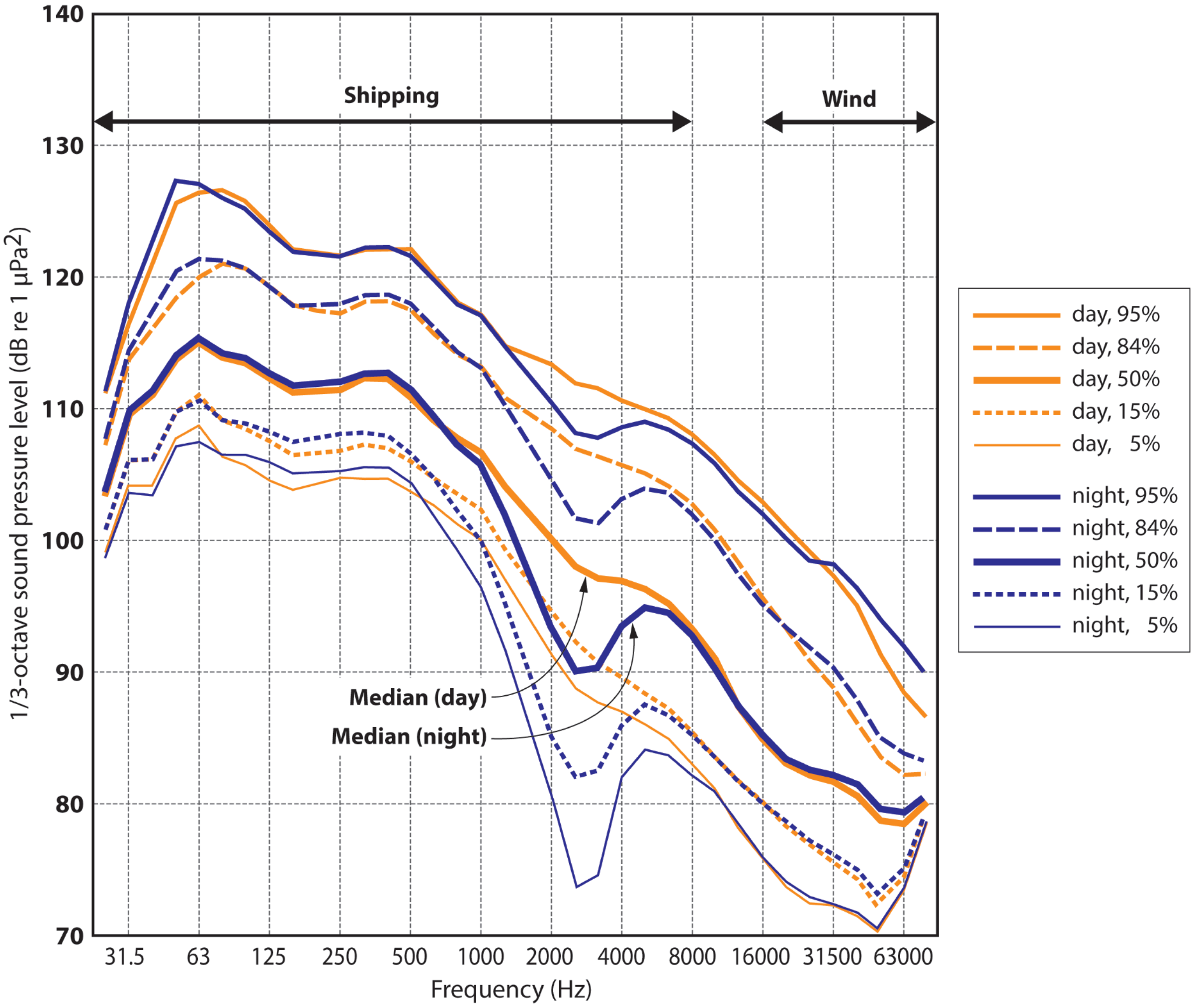


**Figure 3.6:** *Temporal variability in sound spectra (sound pressure level in 1/3-octave bands) during a one-week recording of ambient sound close to the Port of Rotterdam, including shipping-generated sound below 10 kHz, mostly due to dredging activity, and wind-related sound above 20 kHz. Strong diurnal changes in shipping sound are attributed to fish with air bladders, which absorb sound efficiently when dispersed at night (from Ainslie et al., 2011). Used with permission from the authors and the organizers of the Underwater Acoustic Measurement conferences.*

The intrinsic characteristics of the sources (in terms of factors such as spectral content, time evolution, radiation pattern) need to be characterized independently based on the way in which that sound is modified as it propagates through seawater, especially for physically large sources such as ships.

Nevertheless, in spite of our goal to characterize the sources that make up soundscapes, most existing studies represent soundscapes in terms of a spectrogram (e.g., Figures 3.1 and 3.5) and the motivation is to disaggregate the contributing components from a complex soundscape measured at a specific time and location. This approach has attracted a large amount of attention in the past because of the importance of localized sound sources in military applications used for detecting the signal of a submerged object from within the background ambient noise. Defining the position and main characteristics of contributing sources (in particular anthropogenic ones) relies on accurate modeling of sound propagation from the source to the measurement location, based on representative modeling of oceanographic features affecting sound propagation, such as wind speed (Figure 3.4; Nystuen et al., 2008), wave height, sound velocity profiles, ocean bathymetry, and sediment type.

It will be challenging to design systems that classify sound sources based on all available a priori information that could help in resolving the problem, such as oceanographic measurements, visual observations, ship tracks from the Automatic Identification System (AIS), and information about the presence of other industrial activities such as pile driving (Figure 3.3a) or seismic surveying. Access to historical data may allow post hoc analysis. The identification of sound sources will need to rely on access to central libraries of recorded and identified sounds.

Automatic detectors and classifiers can be used for streamlined analysis of data. Classification systems will form an important part of the IQOE. Several commercial or open-source software tools are available for detecting, localizing, and classifying marine mammal sounds in real time or as a post hoc system for analyzing detections using WAV files. Individuals can design detectors for any sound source and load them into open-source software tools, broadening their applicability for the IQOE. Databases are also critical for validating detection and classification systems. For example, Mellinger and Clark (2006) describe an online database of low-frequency calls of baleen whales.

### *Key questions*

Relevant questions related to understanding variation in ambient sound include the following:

- Can sound sources be classified into broad groupings that will provide sufficient detail to enable the construction of predicted ambient sound maps?
- What are the important sound sources for which we have insufficient information about both the sounds they produce and their distribution?
- What patterns in the behavior of sound sources and sound propagation are important to predict the underlying causes of ambient sound variation?

### *Research approach*

The number and type of potential sound sources are almost limitless, making it impracticable to include every individual source in models to estimate soundscapes. In such situations, modelers often include a small number of representative elements in their models, scaling up individuals to populations based on estimated numbers or densities of individuals. The IQOE modeling activities will use such an approach, selecting a small number of representative examples of the three main classes of sound sources: physical, biological (Figure 3.7), and human-generated. For example, a model soundscape might include one or two species of baleen whales, one dolphin species, one fish species, a small number of storms in specific areas, and a few types of ships, naval sonars, and seismic surveys in specific locations.

**Figure 3.7** *Examples of biotic contributors to ocean sound.*
*(top) Blue whales* (Balaenoptera musculus). *Credit: NOAA: http://www.afsc.noaa.gov/nmml/gallery/cetaceans/blue-6.php, (lower left) Snapping shrimp* (Alpheus lottini)*: http://smithsonianscience.org/2012/03/preventing-home-invasion-means-fighting-side-by-side-for-coral-dwelling-crabs-and-shrimp/, (lower right) Atlantic croaker* (Micropogonias undulatus)*: EFSC Pascagoula Laboratory; Collection of Brandi Noble, NOAA/NMFS/SEFSC. http://commons.wikimedia.org/wiki/File:Fish4327_-_Flickr_-_NOAA_Photo_Library.jpg*

For physical sources of sound, we will explore further examples of the use of wind data as a proxy for sound produced by weather and examine the extent to which the relationship between wind speed and ocean sound is consistent among these examples. A further factor determining sound levels in polar waters is that associated with ice movement and breakup. However, we will also test the hypothesis that this sound is related to wind speed. The sound produced by sea ice can take many forms. For example, during winter, thermal cracking is a major source, especially during clear nights (in this sense the sound is dependent on the weather). Ice fracture and compression-related cracks produce distinctive signals that depend on the larger-scale current and wind stresses. The closing of winter also produces a distinctive sound. Interaction of ice floes in the marginal ice zone is affected by wind and waves and is the source of significant sound. An important further source of sound is the noise generated by icebergs (Figure 3.8) as they calve and break up, and ice sheets as they are moved by tides and winds.

Databases and libraries, or links to existing databases and libraries, of appropriate sounds will be created on the central data Web site for the IQOE by building on the Aquatic Acoustic Archive (http://aquaticacousticarchive.com/) and the MobySound (Mellinger and Clark 2006) archives that have already been created.

Furthermore, we will support the continuation of the *ad hoc* Detection-Classification-Localization (DCL) Workshop series, including researchers with a common interest in the detection and classification of marine biological sound, especially from marine mammals. Six workshops have been held in this series so far, the most recent in 2013 (see http://www.onr.navy.mil/reports/FY13/mbgilles.pdf). In this context, we will also support the further development of appropriate software systems for data collection and off-line analysis.

**Figure 3.8.** *The IQOE will estimate the contribution made to ambient sound by the breakup of Arctic ice floes. Photo by Brocken Inaglory, Creative Commons Attribution-Share Alike 3.0 Unported license.*

## 3.3 Modeling soundscapes (sources and propagation)

Information about ocean soundscapes can be used for different purposes. Biologists often want actual time-series data, representing precisely the sounds heard by whales, fish, and other organisms in the marine environment. This allows careful analysis, for example, of how shipping sound might mask communication between animals, or interfere with foraging. On a much broader scale, the sound power can be averaged globally and annually to describe trends (see Section 3.1) or determine sound budgets. The sound sources span a wide range of frequencies from the low-frequency rumble of earthquakes, the drumbeat of seismic air guns, and the churning sounds of ship propellers, to mid- or high-frequency sonar pings and the even higher frequency foraging clicks of marine mammals.

Significant effort has been devoted over the years to developing sound propagation models, mainly for naval applications. As a result, regions outside those of naval interest are sometimes poorly modeled; for example, an adequate model for range-dependent acousto-elastic environments (such as sandstone and limestone seafloors, or tropical reef environments) is still lacking. Furthermore, much of the navy-driven work has focused on detecting extremely quiet sources (submarines) by listening for them against the background of these other masking sources. Thus, the focus of modeling efforts essentially reverses foreground and background.

Modeling soundscapes is carried out using a variety of sound propagation models (Frisk, 1994). This requires information about sound sources (see Section 3.2) and about the structure of the ocean through which the sound is likely to travel. The prediction of propagation depends on the specific model used—and there are many from which to choose—and the characteristics of the environment. The models normally work by simulating the path of sound through water in two-dimensional slices radiating away from the sound source. As sound encounters different discontinuities, such as the surface, the seabed, or an ocean front, its path is determined by the characteristics of the discontinuity due to diffraction or reflection. The gradient and position of the thermocline as well as the density of the seawater, determined by measuring temperature and salinity changes with depth, therefore are important input variables within these models.

Consequently, to predict the propagation of a known sound in the ocean accurately, the following information is needed: (1) ocean ”weather” or oceanography in terms of its temperature and salinity structure; (2) sea state in terms of surface wave and wind-generated bubble conditions; (3) water depth or bottom topography; and (4) geoacoustic sub-bottom structure in terms of the density, sound speed, shear wave speed, and attenuation of sound in the sediment. Sound speed in the ocean is also affected by pressure, creating areas of the ocean in which sound can be trapped in “waveguides” and propagated for long distances. Sound waves refract and reflect, much as light waves do.

Global bathymetry is probably the most readily available data, through sources such as the National Geophysical Data Center in the United States. International consortia (HYCOM, Mercator, and FOAM) provide global forecasts of oceanographic information. Global sources of information for the sea state need further investigation; however, satellite data often can give information about the roughness of the sea surface.

One of the biggest challenges in modeling soundscapes is to model the ocean bottom reflectivity accurately. Some limited global databases of ocean bottom composition are available. It may be possible to learn more about bottom reflectivity from existing sound sources (e.g., shipping traffic), reducing the need to add new sources. Exploiting this information to characterize the seabed, as well as the structure of the ocean, is an innovative challenge for the IQOE (Gervaise et al., 2007).

Overall, there will be a need to develop approaches to modeling that use approximations for information required. For example, we are uncertain how precisely variability in oceanic conditions will need to be specified for investigations of general questions at large spatial scales. Will it be necessary to specify ocean weather conditions precisely, or can functional relationships between ocean sound and wind speed provide an appropriate surrogate for ocean weather (see Section 3.2)? The precision of inputs necessary at any desired scale, and the uncertainties involved, will need to be specified.

Modeling the propagation of sound to characterize soundscapes is feasible at large scales within the open ocean. However, the complexity of shallow coastal environments will make it immensely difficult to develop useful predictive models in such areas. Instead, sound propagation models have been run on independent bearing lines assuming that the sound stays in a single two-dimensional vertical slice. The IQOE will encourage the development of modern advances in three-dimensional sound propagation modeling (Figure 3.9). A considerable factor in the uncertainty in these models is information about the sediment type and its acoustic reflectance and this uncertainty points to a need for improved integration of information about the geomorphology of the seabed to sound propagation models.

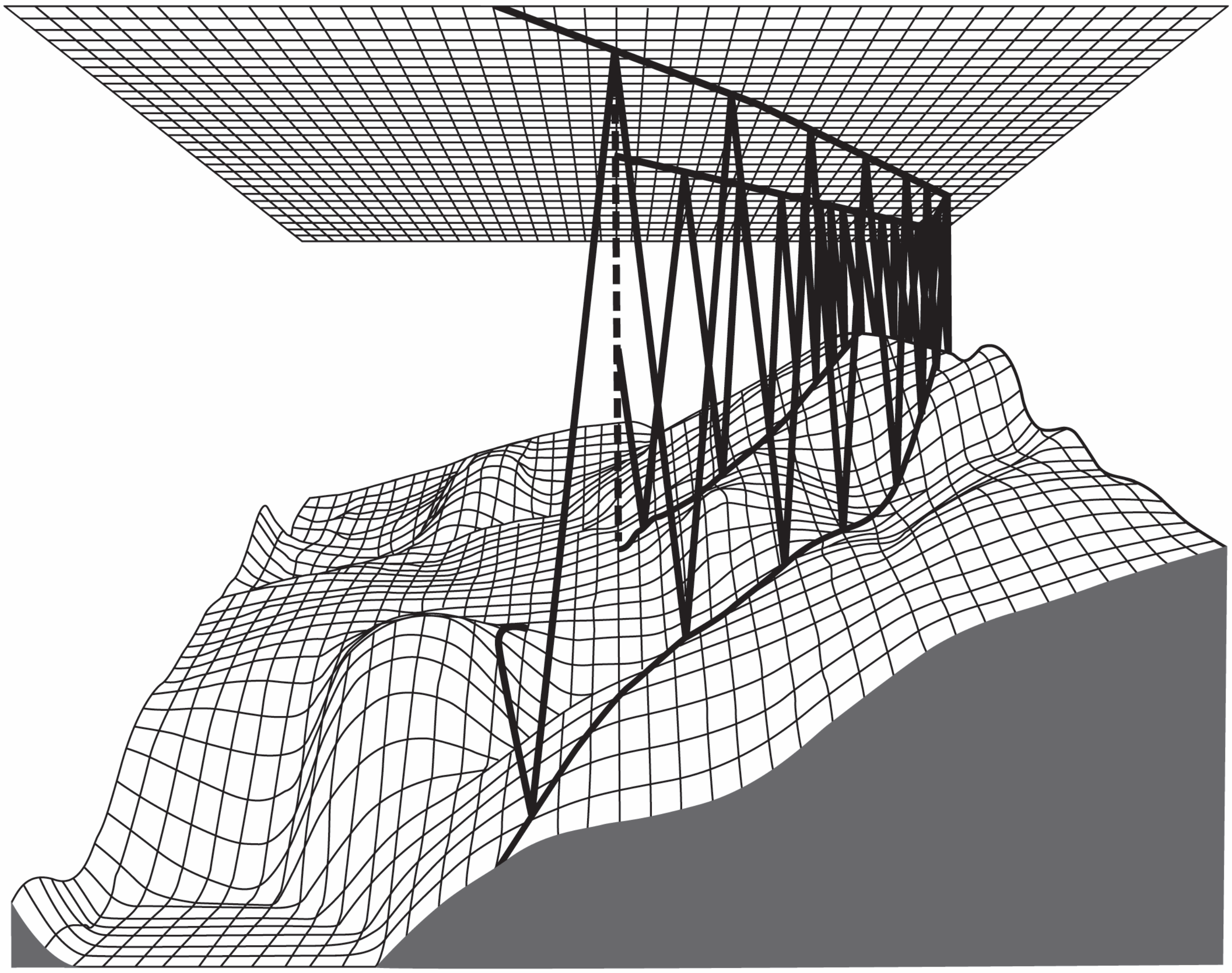

**Figure 3.9.** *Rays of sound, illustrating horizontal refraction, traveling over a complicated topography that produces three-dimensional effects, illustrating a model of a beam trace for shallow water near Hawaii. Permission from Bucker (1994). Copyright 1994, Acoustical Society of America.*

By making several broad assumptions, it should be relatively easy to generate soundscape models, but validation of these models will be much more difficult. The process of generating models will probably be most easily accomplished at large spatial and temporal scales but validation data, most probably generated through ocean observation (see Theme 3), will be most relevant to smaller spatial and temporal scales.

There will be a discrepancy between the spatial scales at which soundscape models are likely to be developed and those associated with data collection. This is because data are almost always collected at single locations and the extent to which that location can be used to validate models will vary with sound frequency. Point observations will be less effective for validation as frequency increases. Consequently, validation may most likely succeed initially at lower frequencies.

Model validation may be possible by fitting the model results to observations. Since the models themselves can be generated independently of the observations, it should be possible to establish Bayesian fitting procedures for soundscape models. Not only will this allow generation of an expression of the accuracy of models because the output will be a statistical distribution, but it will also help to further define the parameters in the soundscape models that provide most information.

Experimental validation is the ultimate test. To achieve effective validation, it is necessary to be able to separate the individual components of the soundscape. This will require a variety of sensors, including horizontal and vertical line arrays, as well as vector sensors that respond directly to the particle velocity field sensed by many species of fish.

Site selection is also a key part of the validation. Sites in the Southern Ocean where human contributions are less important will be useful to assess the prediction of naturally occurring sound due to storms, lightning, wind, etc. In particular, a site under the Ross or Filchner ice shelves could provide a unique opportunity to establish conditions that would allow calibration of the ambient background sound level without contamination by local biotic or abiotic sounds. These sites are essentially 1000 $km^2$ caves isolated from anthropogenic sources of sound and that have their entrances pointing toward the South Pacific and South Atlantic oceans. However, specific recommendations about sites should emerge from a process that evaluates a set of alternatives and provides logic for the selection(s).

***Key questions***

Relevant questions related to modeling soundscapes include the following:

- To what extent can existing models be used to characterize global soundscapes and estimate the uncertainties within the models?
- What are the limits of modeling in terms of the scales at which it is possible to obtain reliable results and how does this vary between contrasting locations (e.g., offshore versus coastal)?
- What sampling is required for key parameters to characterize the main sources of sound?
- What sampling is required for key parameters to characterize the propagation medium?

***Research approaches***

We will establish a modeling working group to exploit situations in which it may be possible to test the validity, as well as the uncertainty, in different models. Ensemble modeling, the use of multiple models to evaluate specific scenarios, will be used to examine the influence of model structure and assumptions. This model validation may be carried out in conjunction with other studies in the Effects of Sound on Marine Organisms and the Ocean Observation themes (Themes 2 and 3, respectively). There may be areas, such as ice shelves in the Antarctic or isolated regions that are known in considerable detail and are acoustically quiet, like the Tongue of the Ocean, that provide opportunities for model development and validation. Indeed, the U.S. naval underwater ranges may be ideal for this purpose because of the hydrophone arrays present and the high level of knowledge of acoustic propagation conditions in these locations. Some biologically important areas, such as shallow coastal areas, are particularly difficult to model and will require extra effort.

The IQOE also wishes to support the development of new models that include three-dimensional capability and that are dynamically linked to oceanographic models (Theme 3), as a way of developing improved real-time model performance.

## 3.4 Influence of climate change

The Earth's changing climate is resulting in increasing acidity and temperature of the upper ocean. The increasing temperature also is causing melting of polar ice caps and possibly increasingly frequent tropical storms. These changes can affect the soundscape in many different ways:

- Increasing average wind speed (Young et al., 2011) might lead to increasing contributions to noise from breaking waves and decreasing contributions from other sounds if these are weakened by surface scattering (Weston and Ching, 1989).
- The periods and areas for which sound is affected by melting ice will change. Changes in salinity will change sound propagation.
- Increasing acidity might lead to increased acoustic transparency (Hester et al., 2008; Brewer and Hester, 2009). Although theory suggests that pH changes have had a negligible effect to date (Joseph and Chiu, 2010), the possibility remains of a larger increase in the 21st and 22nd centuries (Ainslie, 2012).
- Increasing temperature might have at least two offsetting effects:
    - Increasing sound levels due to increasing transparency.
    - Decreasing sound levels due to increased average surface sound speed (Ainslie, 2012).

***Key questions***

Relevant questions related to the influence of climate change include the following:

- Does climate change influence the ocean soundscapes?
- If so, through which mechanisms?
- Is the effect likely to be an increase or a decrease in the level of sound, and over what time scales will any effects be observed?
- Can we control the rate of increase or decrease?

Understanding these influences would open up the enticing prospect of inferring key parameters associated with climate change from measurements of ambient sound.

***Research approach***

The IQOE will investigate the sensitivity of ambient sound to parameters related to climate change (wind, pH, temperature) through models, correlations, and experimentation. Identification of focus areas for regional studies will be based on interests of the scientific community and results of soundscape observations and modeling. A key area for studying climate change effects will be the Arctic Ocean.

# Chapter 4
# Theme 2: Effects of Sound on Marine Organisms

## 4.1 Introduction

Theme 1 projects will deliver comprehensive descriptions of soundscapes. These descriptions will make it possible to predict the sound environment to which organisms will be exposed in specific places at specific times, but this knowledge does not extend to the part of a soundscape that an organism can actually hear and, therefore, how it may be affected. Theme 2 projects will study the responses of marine organisms to their specific "acoustic environments," which are determined by the ability of an organism to hear specific frequencies and sound levels that are part of the soundscape. Each species experiences a different acoustic environment, although similar hearing abilities are often shared by different members of the same taxon. This theme will involve characterizing the hearing abilities of key species and then studying how these species are affected by changes in their acoustic environments, both in their physiology and in their behavior, and how these effects accumulate to produce population-level effects. The theme will include effects from both acute and chronic changes in noise levels.

### *Acoustic environment*

Before studying how sound affects marine organisms, it is necessary to consider how a soundscape—the totality of the sound field within the close vicinity of an organism—translates into a specific organism's acoustic environment. This translation process depends on what organisms hear.

Sounds generated by human activities have changed the soundscape of the ocean, as discussed in greater detail in Theme 1, and modify the acoustic environment of many marine species. The acute, short-term impacts and chronic long-term influences of changes in soundscapes at biologically meaningful scales of time and space, and at meaningful frequencies, are poorly understood. However, there is increasing evidence that animals are responding to and behaviorally compensating for influences from anthropogenic sounds (Tyack, 2008).

Changes in the acoustic environment (primarily increases in human-produced noise) can affect several aspects of an organism's physiology and behavior:

- Increases in sound levels can negatively impact an organism's ability to communicate with others of the same species, its ability to navigate, and its ability to forage for food. The seriousness of the impacts depends on whether the frequencies of human-produced noise are the same as those of the sounds produced by the organism and on the levels of the human-produced noise. This general phenomenon is called "masking."
- Changes in sound levels may directly impact an organism's physiology, such as heart rate and breathing.
- Changes in sound levels may affect an organism's behavior, such as direction and speed of travel, avoidance of noisy areas (which may be preferred habitats), ability to find a mate and reproduce, etc. Changes in behavior may be so extreme as to lead to strandings. Note that sounds such as naval sonar can trigger strandings, even at frequencies far from those of best hearing and of those used by the species that strand (Cox et al., 2006).
- Loud sounds can potentially cause temporary or permanent damage to marine mammal ears or other body parts, although the evidence for such effects in wild populations is limited.

In some cases these changes can have a direct and acute impact on an individual (e.g., a beaked whale responding to mid-frequency sonar, Tyack et al., 2011). Changes in acoustic environment can also have a more indirect and long-term influence on a population, such as prolonged and large-scale reduction in communication space for northern right whales (Clark et al., 2009) and reduction in foraging efficiency in resident killer whales (Williams and Ashe, 2007).

Sound production by human activities becomes biologically significant to an individual animal when it affects an individual's survival or ability to reproduce (generally known as fitness). Because the acoustic environments experienced by different colocated organisms can be very different, sound at particular frequencies has the potential to elicit widely varying responses from organisms of different species and to change the relationships among species in ways that are more complicated than can be predicted by simple dose–response relationships. In some circumstances, sound can change the competitive balance among species, resulting in a cascade of effects within communities (Ruttenberg et al., 2011).

Sound in the ocean modifies the habitats and ecosystems of a broad suite of species, thus amplifying the ecological risk of disturbance and complicating our ability to detect cause-and-effect relationships between other stressors and the responses of organisms. This becomes a particular problem because the largest habitat modifications are likely to occur in the low-frequency range (<300 Hz), over large ocean areas (e.g., ocean-basin scales), and for long periods of time (e.g., months to decades).

Overall, therefore, more research should be focused on the acoustic environments of key marine organisms and how changes in sound affect interactions among individuals and species. The fundamental importance of empirical studies of reactions of species to sound is highlighted by the strandings of beaked whales caused by exposure to sonar. The naval sonars involved have fundamental frequencies well below the lowest frequencies of beaked whale vocalizations, and well below the frequencies of best hearing for beaked whales. On the basis of how beaked whales use and hear sound, environmental analysis might estimate low risk from naval sonars, but exposure to these sonars causes beaked whales in some contexts to strand and die (D'Amico et al., 2009).

***How sound levels are expressed***

An important task of an international project like the IQOE is to standardize how sound levels are measured and expressed by project participants. Acousticians use the decibel scale to represent sound levels; this is a logarithmic scale expressing a decibel value with respect to a reference value. The reference pressure for underwater measurements is 1 Pa, one millionth of a pascal (Pa). A pascal is the Standard International (SI) unit for pressure, expressed as a force per area, 1 Newton/$m^2$. Seawater and air differ so much in density and in the speed at which they transmit sound that it is difficult to compare levels of sound pressure in air with water. An additional complication is that different reference pressures are used for decibel measurements of sound in air and underwater. There is no general method to predict hearing abilities of animals underwater from their ability to hear in air, so attempts to assess the equivalence of sound pressure measurements in air and in water should be avoided.

A critical element of predicting and managing effects of sound on animals involves deriving dose–response functions that relate acoustic dosage to effects on animals. Different measures of sound waveforms have been associated with different effects on animals. The most common measure used in the literature is sound pressure level ($SPL_{rms}$), which is a root mean square (rms) level calculated for the duration of a sound. For effects of impulse sounds, such as sounds of pile driving and explosions, on hearing, the peak pressure can be important. The peak-to-peak pressure is the difference between the maximum and minimum of the instantaneous sound pressure during a specified time interval and is denoted in pascals. The zero-to-peak pressure is the maximum absolute value of the instantaneous sound pressure measured during a specified time interval and also is denoted in pascals.

Invertebrates and most fish species detect the particle motion component of sound. This motion involves small displacement of particles and is often expressed in terms of $nm/s^2$. Some fish have anatomical specializations that allow them to detect sound pressure as well as particle motion (Popper and Fay, 2011). Auditory systems in these species include a connection between the ear and a gas-filled cavity. When sound hits the cavity, the pressure wave causes the cavity to move. These movements cause particle displacement that is then sensed by the fish ear.

***Hearing capabilities and sensitivities of marine organisms***

Marine mammals have ears that detect the pressure wave of sound. Cetaceans are adapted to hear sound underwater, but pinnipeds can hear both in air and underwater. Virtually nothing is known about the importance, if any, of sound to the early life stages of fish and invertebrates, but there is evidence of the capacity of young animals to use sound (Radford et al., 2011).

The sensitivity of hearing of an animal can be represented in an audiogram (Figure 4.1), which shows for each frequency tested, the lowest level of sound that the animal can detect. Audiograms are vital for translating soundscapes into the acoustic environment as sensed by a species. Figure 4.1 shows some audiograms for animals that hear sound pressure underwater. Invertebrates such as the squid or crustaceans do not have very sensitive hearing and cannot hear much above 1000 Hz, or 1 kHz. Invertebrates and most fish only hear the particle displacement component of sound, detecting sound energy as their body moves back and forth in the sound waves. A dense mass (the otolith for fish or statolith for invertebrates) sits on hair cells that sense the inertial force generated between the mass and the moving body. This means that they cannot hear sounds with wavelengths smaller than their body size. With a sound speed in seawater of about 1500 m/sec, this means that a 1.5 m fish would not be sensitive to sounds above about 1 kHz. Fish whose hearing is supplemented by connection to an air-filled cavity can hear higher frequencies, and the closer the connection between the cavity and the ear, the better their sensitivity to sound pressure. Figure 4.1 shows sensitivity to pressure in a variety of fish and mammal species. The codfish (*Gadhus* *morhua*) detects particle displacement below 50 Hz and sound pressure at higher frequencies, so it is valid to display its hearing above 50 Hz on a pressure scale (Chapman and Hawkins, 1973). Popper and Fay (2011) argue that the goldfish (*Carassius auratus*), a much smaller fish, senses particle displacement below 500 Hz, but has a more direct anatomical connection between a gas-filled cavity and the ear. Comparing the audiograms for cod and goldfish shows that the goldfish with the more direct connection appears to be more sensitive and have better high-frequency hearing. Some clupeid fishes are sensitive to frequencies as high as those used by odontocetes for echolocation (Mann et al., 2001); this specialized hearing is thought to warn the fish of an oncoming predator.

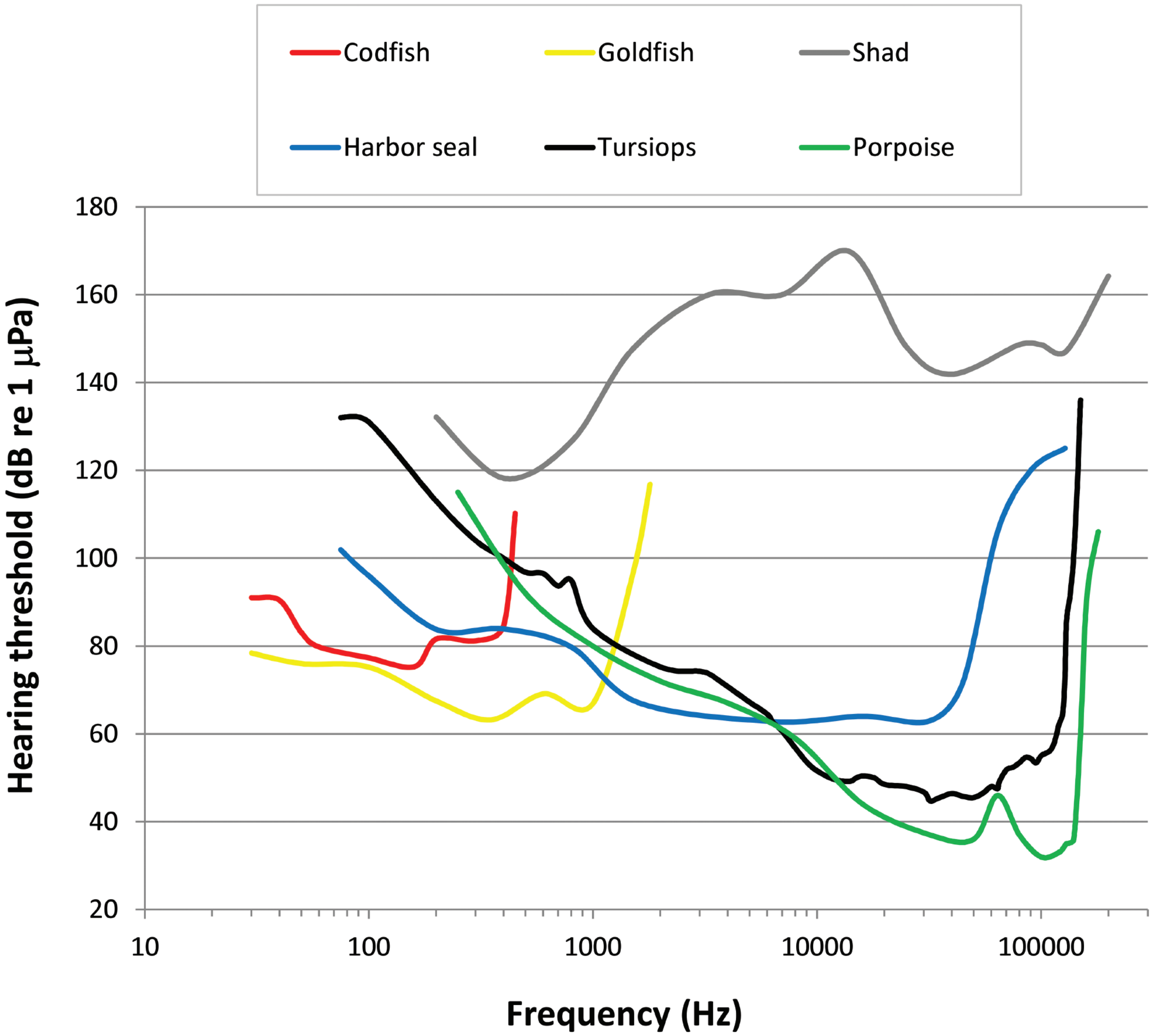


**Figure 4.1.** *Representative hearing thresholds (audiograms) of a range of marine organisms. Data from Johnson (1967:* Tursiops: *bottlenosed dolphin); Møhl (1968: harbor seals); Fay (1969: goldfish); Chapman and Hawkins (1973: codfish); Mann et al. (1997: shad); Kastak and Schusterman (1995, 1998: harbor seals); and Kastelein et al. (2002: harbor porpoise).*

Pinnipeds are amphibious and have hearing adapted for listening in air as well as in water. The toothed whales use echolocation to orient, find, and capture prey. As with bats, echolocation has selected for high-frequency hearing; small porpoises are specialized for particularly high hearing ranges and delphinids for a medium range between that of the pinnipeds and that of porpoises. Hearing has never been measured in baleen whales, but their use of sounds in the 10-

1000 Hz range and the anatomy of their ears suggest that they are low-frequency specialists (Ketten, 2010). Seals can hear frequencies underwater ranging from about 75 Hz to 75 kHz, while most toothed whales and dolphins are thought to hear from about 200 Hz to 200 kHz. Their use of echolocation favors highly sensitive hearing at unusually high frequencies. The porpoises and several dolphin species use narrow-band high-frequency echolocation signals and appear to have hearing particularly specialized for high frequencies.

To correct sound exposure for the frequency range of hearing for different taxonomic groups of animals, it is possible to apply weighting functions to filter sound energy and predict the potential impact on these taxa (e.g., Southall et al., 2007; Figure 4.2). Other approaches have been suggested, such as Tougaard et al. (2014).

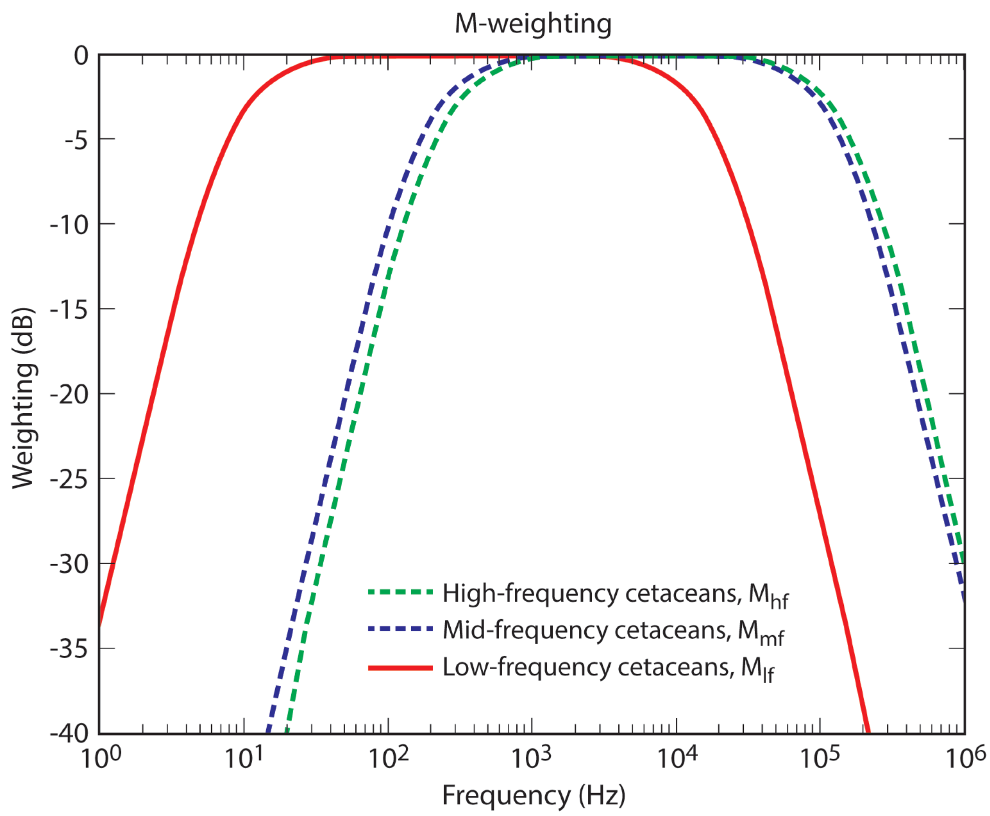


**Figure 4.2.** *Weighting curves suggested by Southall et al. (2007) to filter sound signals by the hearing capabilities of different cetacean taxa. Permission to reuse figure granted by the journal* Aquatic Mammals *and the authors.*

### *Sound exposure levels*

To define criteria for sound exposures that damage hearing, Southall et al. (2007) reviewed experiments that quantified temporary reductions in hearing sensitivity after measured exposures to sound. The longer the exposures were, the lower the sound pressure levels required to cause the same hearing loss. The sound exposure level (SEL) is an acoustic measure that is useful for accounting for this relationship between level and duration. The sound exposure level for a sound of duration T is the equivalent sound pressure level (SPL) if the sound had a 1-second duration. Southall et al. (2007) advocate using an exposure criterion for hearing damage based on sound exposure level weighted by the frequency range of hearing. They also add a second criterion of peak pressure level unweighted by hearing curves, as sudden intense fluctuations of pressure can also damage the ears of marine organisms.

### *Effects of anthropogenic sound on marine organisms*

Relatively little is known about the effects of anthropogenic sound on marine organisms, in relation to what we need to know. The hearing thresholds of most marine organisms have not been precisely described. Although there is considerable knowledge of the anatomy of auditory systems in marine vertebrates (Fay and Popper, 2000; Ketten, 2010) and of the mechanics of hearing, important uncertainties remain regarding the diversity of frequency-dependence of hearing capability, as well as hearing sensitivity, in many species. Even in species whose hearing capabilities have been studied in considerable detail, mainly a few fish species and a small number of marine mammals, little is known about how hearing varies with age and other life-history features, such as sound exposure history.

*Invertebrates*—Most invertebrates are thought to detect particle motion (Budelmann, 1992), but there is relatively little understanding of their hearing capabilities.

*Fish*—Fish detect particle motion as well as sound pressure (Popper and Fay, 2011). Popper and Hastings (2009) reviewed the literature for fish and concluded that little is known about the effects of anthropogenic sounds on fishes, and that it is not yet possible to extrapolate from the results of one experiment to other parameters of the same sound, to other types of sounds, to other effects, or to other species. This is a typical situation.

*Marine Mammals*—More is known about effects of sound on marine mammals (Southall et al., 2007) than on invertebrates or fish. The earliest studies focused on behavioral responses that were obvious to visual observers. The most common response observed was avoidance. While avoidance can cause animals to leave preferred habitats, few studies have actually measured whether avoidance forced animals to move to suboptimal habitat. Other responses have been interpreted as disturbance responses. For example, U.S. permits for marine mammal research list "breaching, tail lobbing, underwater exhalation" as strong adverse reactions to vessels. Many papers report specific cases in which such behaviors were associated with some human activity, but there have been fewer studies structured to test whether the rate of these behaviors was actually higher during exposure to disturbance. The only case of lethal behavioral reactions of cetaceans to anthropogenic noise involves atypical mass strandings of beaked whales that occur during naval sonar exercises. Correlational studies have demonstrated a statistical association between these strandings and sonar exercises in several sites around the globe (D'Amico et al., 2009; Filadelfo et al., 2009). However, there has been growing understanding that disruption of critical activities may be just as important as documenting acute responses. For example, Miller et al. (2009) found a reduction in swimming effort accompanied by an apparent reduction in foraging when sperm whales were exposed to seismic surveys, and Goldbogen et al. (2013) found a similar effect of naval sonar on foraging blue whales. Any disruption of critical activities—such as foraging, migrating, avoidance of predators, or group cohesion—could pose more significant risks to individual animals and populations. Acute effects have been summarized by Southall (2007), but there are few systematic studies on whether and how anthropogenic sound may disrupt critical activities. For example, the effects of masking of communication by anthropogenic sound and chronic disturbance of normal activities by sound are poorly understood.

***Dose–response curves***

Dose–response curves have also been estimated for behavioral responses of marine animals to underwater sound. For example, Miller et al. (2014) estimated the sound pressure level of naval sonar likely to cause avoidance reactions in killer whales. In an extensive review of the literature, Southall et al. (2007) found that $SPL_{rms}$ was the most common acoustic parameter reported for sound exposures. The precise parameters of acoustic exposure that lead to response have seldom been tested, and are likely to vary depending on nonacoustic contextual parameters as well (Ellison et al., 2012). For perception of loudness, the mammalian ear tends to integrate sound energy over periods of 200-500 ms (Southall et al., 2007) and over frequency bands of about 1/3 octave. These results suggest parameters for estimating the loudness of a signal as perceived by a marine mammal. However, responsiveness to sound may depend on details of the waveform (e.g., does it sound like a predator?), the state of the animal (already stressed?), and the behavioral context (feeding? traveling?). In spite of our understanding that many factors influence behavioral responses, most studies of dose–response relationships emphasize a univariate response to an acoustic parameter like the one illustrated in Figure 4.3. The derivation of these types of relationships is central to predicting and managing the effects of anthropogenic sound on marine organisms.

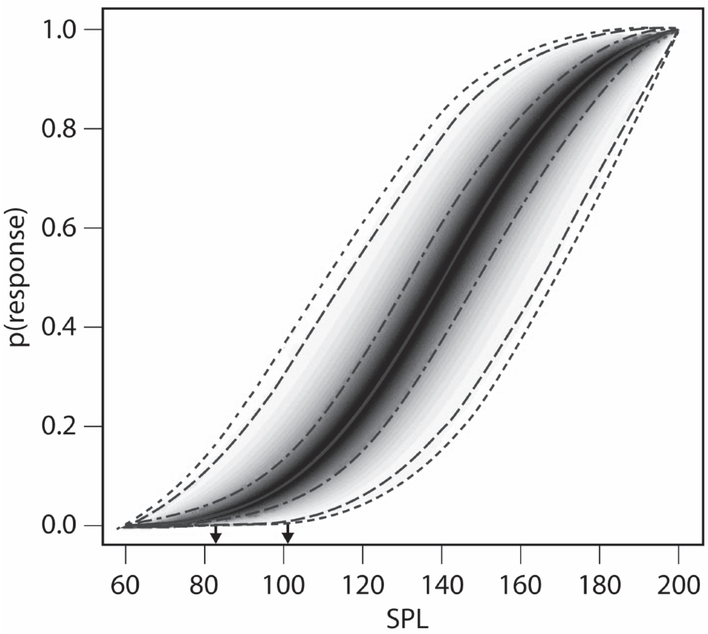


**Figure 4.3.** *Posterior dose-response curve showing the probability of onset of avoidance against received SPL (dB re 1  Pa). The solid central line represents the mean, followed by 50%, 95%, and 99% credible interval lines. The dose-response model assumes the signal is audible over the range, but the limited data on the threshold of hearing for 1−2 kHz signals by killer whales indicates that sensitivity ranges from 101 dB re 1  Pa at 1 kHz to 83 dB re 1  Pa at 2 kHz (marked in the figure with small arrows). Used with permission from the Acoustic Society of America.*

In some cases, responses are defined by physiological criteria, such as permanent or temporary threshold shifts (Southall et al., 2007). But functions relating behavioral responses to acoustic exposures, such as the black curve for avoidance responses of killer whales in Figure 4.3, are increasingly recognized as important. Exactly which threshold is most important will vary with the signal being tested and with species and circumstances, but in general, we need more information to create these kinds of response functions. Similarly, although Figure 4.3 shows "avoidance" as the response criterion, where this signifies a change in behavior as a result of sound exposure, many other criteria could be used; establishing which criterion is most important biologically, as opposed to which is most easily measured, will make a considerable difference to assessments of the effects of sound on the life functions of marine organisms (see Figure 2.4).

***Regulatory use of noise measurements***

A variety of jurisdictions have established regulatory criteria for the effects of sound on marine life. The regulator in the United States, the National Marine Fisheries Service (NMFS), has established criteria for "takes" under the Marine Mammal Protection Act (MMPA). For example, NMFS has established that exposure of harbor porpoise (*Phocoena phocoena*) to SPLs above 120 dB re 1 μPa are likely to cause behavioral harassment, a "level B take" under the MMPA. Similar exposures above 140 dB re 1 μPa are assumed to cause behavioral harassment in beaked whales. These takes of individual animals are prohibited by law, and are regulated whether they have long-term impacts on populations or not. By contrast, the Marine Strategy Framework Directive (MSFD) of the European Union (EU) focuses on measuring noise levels instead of actual effects of sound on animals (Van der Graaf et al., 2012). The MSFD proposes to monitor for good environmental status by measuring average $SPL_{rms}$ in two-third octave bands at 63 and 125 Hz, thought to indicate noise from shipping that will propagate long distances. Management actions under the MSFD are likely to focus more on limiting noise exposure rather than limiting effects on wildlife as in the U.S. regulatory framework.

The kind of soundscape information provided by the IQOE from activities as part of Theme 1 should be helpful for managers to evaluate, support, and improve some of the noise monitoring requirements established by the European Union. However, effective protection of marine life from adverse effects of underwater sound will require an understanding of what sound exposures pose what kinds of risk. That kind of understanding will result from activities as part of Theme 2. The IQOE will make it a priority to improve the definition of the response functions for key species, especially keystone species within ecosystems, commercially important species, and species of conservation concern.

## 4.2. Hearing capabilities of key species and experimental methods for establishing functions relating acoustic exposure to behavioral responses

***Key questions***

- What are the hearing capabilities of key species?
- How can dose–response functions be created and expressed in forms that are scientifically accurate and meaningful for management decisions?

Fundamental to relating soundscapes to individual organisms and populations is to determine the acoustic environment for a species, the parts of the soundscape that the species can actually hear. The ideal way to objectively quantify the hearing capabilities of any organism is to directly measure responses to a range of frequencies and sound levels, that is, to create an audiogram for the species. NRC (2000) recommended that U.S. federal agencies sponsor collection of audiograms from large samples of multiple individuals of different ages and both genders, including stranded and rehabilitating marine mammals.

Ideally, multiple individuals should be tested, over a range of ages, including both males and females, to describe an average or typical audiogram, and also the ranges in hearing abilities that may be present in a population. Most organisms cannot verbalize when they can hear or do not hear a sound, so other means of detecting whether a sound is audible need to be employed. Some marine mammals have been trained to indicate when they hear a sound. White (beluga) whales were trained by U.S. Navy scientists to indicate heard sounds at various depths in the open sea (Ridgway et al., 2001). Most other audiometric measurements that involve training have used animals in captive settings.

It is difficult or impossible to train most marine mammals, and particularly the larger toothed and baleen whales, to indicate what sounds they can hear. In these cases, it has occasionally been possible to test for "auditory evoked potentials" as the brains of organisms are exposed to sounds and brain reactions are measured. This technique, also used by physicians to test the hearing of newborn infant humans, has been used on stranded and rehabilitating marine mammals to test their hearing ability. For example, Nachtigall et al. (2005) determined the audiogram of an infant Risso's dolphin, Yuen et al. (2005) determined the audiogram for a false killer whale, and Castellote et al. (2014) used evoked potentials to test the hearing of beluga whales. Admittedly, the audiograms may represent the hearing of distressed individuals, but they correlate well with measures based on behavioral responses (Nachtigall et al., 2007).

Finally, the most widely used experimental method of testing whether specific sounds evoke specific behavioral responses of animals in the wild is to play sounds to a subject and look for behavioral responses. In free-ranging animals that are submerged at the time of exposure to sound, it may be difficult to observe behavioral responses directly and to obtain real-time feedback about the dosage given. A recent approach to resolving these problems has been the deployment of receivers on larger marine mammals that can both hear the sound sources (and thus measure received levels) and detect behavioral changes due to the sounds. This method often involves attaching a tag to each experimental subject. A typical tag for large whales is described by Johnson and Tyack (2003), but may require modification for each species, and in many cases it may not be feasible to manufacture tags small enough to attach to the animals of interest. In these circumstances, alternative methods for recording the received sound and the animal's response will be required. The tag described by Johnson and Tyack (2003) was designed to record sound and behavior throughout the dive cycle of a whale even when animals are deep and out of view. Nonacoustic sensors also recorded depth, temperature, orientation, and acceleration of the whale. These nonacoustic sensors were sampled rapidly enough to capture fluke movements and swimming behavior, along with subtle changes in orientation. These types of tag are capable of simultaneous measurement of the dose of sound received and the behavioral response of the animal.

Under specific circumstances, there may be opportunities to conduct experiments that have a considerable level of control, for example, through controlled exposure experiments (CEEs). Although the IQOE will attempt to develop protocols that do not require the addition of sound to the ocean, some of the most successful recent studies have involved examining the response of animals to carefully controlled doses of sound (e.g., Tyack et al., 2011; DeRuiter et al., 2013). Controlled exposure experiments use well-established methods in the behavioral sciences to study the responses of animals to stimuli. When acoustic stimuli are used, the method is usually called a "playback experiment." An extensive literature documents the design of playback experiments (e.g., Kroodsma, 1989, 1990; Kroodsma et al. 2001; McGregor, 1992, 2000; Wiley, 2003). Classic playback experiments are only concerned with measuring and evaluating different responses to different stimulus types. The added features for controlled exposure experiments on sound involve controlling the level of exposure at the animal, and determining the minimum sound level that starts to elicit a response. The protocol normally achieves this goal by slowly increasing the received level at the animal from a level near what is just detectable until the animal responds, or a maximum planned level is reached (Tyack et al., 2011). This dose escalation ensures that the exposure at each animal is the minimum required to define the dose–response relation and to measure the response. If any such experimental studies are judged to be essential for resolving critical uncertainties about effects of sound on marine animals, for the IQOE to support them, they would have to involve sound exposures that are sufficiently limited in intensity, range of detection, and duration that they would be expected to have minimal effects beyond the specific question being studied, and the link between exposure and effect could not be demonstrated by using ongoing exposures.

Box 4.1 includes several detailed questions about effects of acoustic exposure.

**Box 4.1.** *Examples of questions to be addressed on the topic of dose–response relationships*

- **Physical and physiological effects**
  - Does background sound cause masking of animal communication and, if so, to what extent?
  - Do animals compensate for masking?
  - How do we measure or assess how the received sound is perceived by the animal? Does this change with environmental context?
  - Which animals are more susceptible to intense sounds, such as naval sonar or sounds used for seismic surveys? For example, are large whales more susceptible than small whales or fish?
  - What frequencies can be heard by various species of marine life? What are their audiograms?
  - How can we best estimate the hearing range of animals, for species where hearing cannot be measured directly?
  - Can hearing damage from sound be modeled?
  - What impact does long-term sound exposure have on the hearing ability of marine life? Is there an effective recovery period?
  - Could anthropogenic sound sources cause animals to become frightened, resulting in decompression sickness in the case of air-breathing marine organisms?
  - What are the impacts of industrial sounds on fish and turtles?
  - What are the impacts of industrial sounds on invertebrate species?
  - What is the relationship between equal loudness curves and audiograms?

- **Behavioral effects**
  - What aspects of the sound source are responsible for behavioral response: sound exposure level, peak pressure, frequency content, harmonic context, texture, etc.?
  - What behavioral responses occur when animals are exposed to anthropogenic sound sources?
  - How do anthropogenic sound impacts vary by species and environmental context?
  - Do long-term industrial operations have impacts on animal residency? If so, which species are most affected and to what extent?
  - What is the impact on animal populations of the masking of sound used for communication and echolocation?
  - Do animals become sensitized or habituated to repeated particular sound exposures?

*Controlling the dose*—Controlling the dose of sound received is an important component of a CEE. Since, for some species, high doses of sound could be damaging, the basic principles for achieving a balanced dose–response involve the following steps:

- Monitor response in real time.
- Establish a mechanism to cease exposure or prevent increases in the exposure level if response reaches a preset threshold.
- Evaluate the response for risk before increasing the duration or intensity of exposure.

Another concern is the need to control potential exposure for animals that are not the focal subjects. In free-ranging conditions it is possible that nonfocal individuals within a population will receive a greater dose than the focal animal. Monitoring efforts need to be put in place to reduce this risk.

*Control subjects*—Experimental designs require control subjects in addition to subjects exposed to a particular dosage range. Depending on circumstances, these could be unexposed individuals within the population or, probably more often, individuals will act as their own control. In these circumstances, the most critical part of most CEE designs is the ability to monitor specific animals' undisturbed behavior before exposure to a sound, followed by detailed monitoring of their responses during and after exposures. This before/during/after design is especially useful where there is a high variance among individuals in expected behavior, but it requires in the subsequent analysis that the identity of each individual be included as a covariate.

*Control stimuli*—While an experiment may be designed to examine the response to a primary stimulus (such as sonar sound, ship sound, or pile driving), every controlled exposure experiment also requires control stimuli. One standard "silent" negative control stimulus would involve following the protocol in its entirety but without transmitting the signal of interest. There are also questions about how specific any observed response might be to the primary stimulus and, where this is important, a negative control stimulus should be used with the same timing and frequency range as the primary stimulus, but with band-limited noise instead of a specific waveform.

***Research approaches***

*Hearing*—The first task in approaching this key question is to compile all available data on hearing capabilities of marine organisms, including all the audiograms. A workshop will be held to discuss the available data, synthesize it, identify gaps in the data, discuss the potential list of representative species below, draft a review paper for the peer-reviewed literature, and develop an implementation plan for this key question.

A set of representative species, for which audiograms or other measures of hearing capabilities will be developed, should be identified. The following is a representative list of potential species. Audiograms for a few individuals already exist for some of these species, but more individuals should be tested. In some cases, this will require the development of new equipment and new techniques.

- Baleen whales: blue whale, northern/southern right whales
- Toothed whales and dolphins: killer whale, bottlenose dolphin, harbor porpoise
- Pinnipeds: harbor seal, ringed seal
- Sirenians: dugongs and manatees
- Birds: penguins, auks
- Fish: damselfish, tuna, plainfin midshipman
- Turtles: green turtle, leatherbacks
- Invertebrates (molluscs, crustaceans): squid, ghost crab, lobster, krill

*Dose–response functions*—Defining dose–response functions will require experimental studies of behavioral responses to sound exposure. Controlled exposure experiments may be performed under this theme to create dose–response curves for these organisms, where these experiments will not endanger the test organisms or others. The IQOE will begin to answer the second key question (How can response functions be created and expressed in forms that are scientifically accurate and meaningful for management decisions?) by convening a meeting of scientists and managers to determine the kind of information that is both relevant to IQOE and possible for IQOE to provide, as well as meaningful for management discussions. This meeting will review and set priorities for cases of putative connections between sound exposure and behavioral responses where experimental studies are required to demonstrate the link and to define dose–response functions. The meeting will be held after the workshop on hearing capabilities.

## 4.3 Effects of changes in acute noise

***Key questions***

The key questions regarding the effects of changes in acute noise are the following:

- What frequencies, sound levels, and durations have effects on the physiology and behavior of key species?
- How do changes in sound levels affect interactions among species?

Section 4.2 discusses experimental methods for demonstrating the link between exposure to sound and acute behavioral reactions. The IQOE will, where possible, emphasize observational studies that do not require the introduction of new sounds. In uncontrolled experiments, significant effects of sound on marine organisms can be difficult to observe. Moreover, effects can be acute or chronic and, in general, it may be easier to observe acute rather than chronic effects. However, experience with some marine mammals (Cox et al., 2006) shows that the occurrence of certain extreme acute effects of sound exposure, such as stranding, can be classified as rare. Many organisms may have thresholds of response rather than a graded dose response (Figure 4.3) and when these thresholds are exceeded an acute intense response may suddenly occur. However, even in these circumstances, acute responses may be context-specific, so that the probability of an effect depends on both the probability of sound exceeding a threshold and the exposure happening in a context in which the animal is susceptible to the effect. Similarly, probability of response can be low at the low end of exposure for a dose–response function. In spite of this low probability, acute effects may still be biologically significant when they occur in species that have relatively low population resilience, such as marine mammals. The majority of previous work on effects of sound has focused on acute effects on behavior that are relatively easy to measure. The IQOE will focus on selecting effects at spatial and temporal scales that are most important to populations and ecosystems.

*Measuring stress*—Behavioral responses to sound exposure or quieting are often observable and measurable responses to anthropogenic sound, but population-level effects of this sound will also be modulated through physiological stress responses. The main stress response in marine mammals is similar to the generalized stress response for other mammals, which is defined by activation of the hypothalamic–pituitary–adrenal (HPA) system in response to an internal or external stimulus (or stressor), resulting in elevated levels of glucocorticoid (GC) hormones (i.e., cortisol and corticosterone). Whether the response is beneficial or deleterious depends on the magnitude and duration of the response and the condition of the animal exposed to the stressor. Prolonged exposure to stress may result in immune system suppression, reproductive failure, accelerated aging, and slowed growth. If GCs are not the primary mechanism, they and other biomarkers may well be indicators of a cascade of effects leading from behavioral changes to alterations in reproduction and survival. However, even among well-studied mammal species, finding individuals exhibiting stress indicators outside the normal range of value for the species may not be indicative of widespread stress because different individuals have widely varying baseline levels of these stress indicators. A recent study suggested that symptoms of stress had been observed in right whales exposed to sound (Rolland et al., 2012), but the changes observed were within the normal range of variation and, while there was an association with a change in ambient ship sound, the relationship was weak. The IQOE will seek to use robust and verifiable measures of stress in organisms to obtain valid evidence of effects of sound on the physiological conditions of organisms.

Stress, measured in terms of similar hormonal indicators, is less well understood in fish and invertebrates. As in mammals, hormones are chemical signals that can have multiple functions operating with different potency on different receptor tissues. The function of hormones is modified through natural selection and through adaptation and acclimation. Consequently, their uses as signals of stress need to be validated carefully. But the concept of stress involving incapacity to adapt or acclimate to immediate environmental conditions is well understood. The ways in which marine species adapt or acclimate to stress are many and varied, and they reflect an underlying complexity of physiological function that may not yield simple indicators of stress related to the effects of noise.

Interpreting point measures of endocrine responses to a stressor requires a good understanding of the natural variation in hormones associated with the generalized stress response. In free-ranging animals, where blood is difficult or impossible to sample, this understanding must rely on collecting biological materials that are more amenable to sampling. Although levels of hormones that potentially indicate stress, such as cortisol in the bloodstream, provide relevant information about stress, accumulation in other tissues and excretions such as blubber, skin, hair, feces, and exhaled breath may provide measures of chronic stress because they are integrated measures of the magnitude and duration of physiological stress responses. Thus, to use stress hormones from matrices beyond blood as indices of stress, the relationship between the levels and dynamics of hormones in blood and other matrices must be determined.

It remains to be seen whether it is possible to define “stress” with sufficient rigor and consistency to make it a general goal of the IQOE to measure stress in marine organisms as a general response variable. In its most general form, stress simply measures an aspect of an organism’s physiology that is outside its normal range. Making and using such measurements will need to be judged based on individual cases and, in some specific circumstances, they may prove to be useful.

***Research approach***

*Selecting key species*—Since different animal taxa may show fundamentally different responses to sound, the IQOE will need to focus on key examples of several different species or taxa. These should be chosen to capture different lifestyles and population demographic features, while representing species for which we have good ancillary knowledge in a variety of study areas and situations, or that are especially amenable to study. Some animals may have a size and physiology allowing for large data loggers to be deployed on them for extended periods (e.g., seals), whereas deployment of large tags can be difficult for other species (e.g., fish, small odontocetes). Some species may have a lifestyle allowing for direct measures of fitness (e.g., damselfish), whereas it may be virtually impossible to measure this directly in others (e.g., baleen whales). Some locations may have patterns of disturbance that are favorable for opportunistic studies (long periods of silence, followed by long periods of activity). The optimal setting for these studies would include several of the best study species in sites where detailed information on soundscapes has been and will continue to be collected. The list of representative study species should be based on a combination of the recommendations of the workshop on hearing capabilities and the results of Theme 1, so that the species with the best information in the best locations can be studied.

*Baseline studies*—Baseline studies provide a quantitative assessment of the normal, undisturbed state of organisms, communities, social structures, and populations. One of the greatest challenges to characterizing baseline conditions is that there may be high natural variability in the parameter(s) of interest. This natural variability makes the detection of changes resulting from the introduction of sound much more difficult because the effect must be differentiated statistically from natural variation. However, depending on what parts of the background variation are important to organisms, the low power of detection does not mean the effects of introducing sound are unimportant. Higher statistical power to detect changes can be obtained by either extending the duration of the baseline observations or by measuring a broad range of covariates alongside the baseline. These covariates could include other potential anthropogenic stressors that may change during the course of the study, but may also include indicators of the natural physical, chemical, and biological characteristics of marine systems. Including such variables within a statistical analysis to look for significant effects from the acoustic exposure may greatly increase the chances of detecting these effects because the analysis controls for the effects of the covariates on the signal of interest. Nevertheless, even in circumstances where no "signal" is detected, there remains the possibility that the signal exists, but there is insufficient statistical power to detect it. Moreover, just because a signal cannot be detected by currently available technology and equipment does not mean it is not biologically significant, and conversely, even if a signal is detected this does not mean it is biologically significant. A key role of the IQOE will be careful selection of study situations that optimize our chances of detecting biologically significant effects at a range of spatial and temporal scales.

The IQOE will include many opportunistic studies. Most will be characterized by some form of observation of marine life and sound associated with a human activity that is generating sound. Observations of this type will be facilitated by the rapid increase in the availability of relatively inexpensive and mobile observation systems (Figure 4.4), which often collect and process data in real time on multiple channels. These multivariate time series, in which sample sizes can be very large, are amenable to the application of statistical modeling to discriminate among effects caused by changes in specific factors, including levels of anthropogenic sound.

**Figure 4.4**. *PAMBuoy is an example of a passive acoustic monitoring system mounted on a moored or drifting buoy that measures marine sounds and carries out acoustic detection and classification of different preprogrammed sound sources. It transmits these in near-real time by cell phone or satellite phone networks to base stations, including cell phones. Source: Sea Mammal Research Unit, University of St. Andrews (see http://www.pambuoy.co.uk/).*

It is probable that relatively few of these studies will provide clear statements of effects and in most cases any effects will be supported to different levels of probability. The value of these studies will be mainly felt through the cumulative weight of evidence they provide, often expressed through meta-analyses.

Ethical and practical constraints often make it difficult to carry out precisely planned experiments on the effects of acute sounds on marine life. Indeed, any experiment conducted in the field is likely to be more or less semiplanned because of the difficulties in ensuring that there are proper control treatments in place. Even in the laboratory, it may often be difficult to conduct fully controlled experiments because of limiting factors such as sample size where, especially for species like marine mammals, few individuals and species are available for study. This can result in biased results because it is impossible to control for individual variation, interspecies differences, and serial correlation within experiments.

Two main forms of unplanned or semiplanned experimental approach can be used. The *comparative approach* has been used traditionally as an empirical method in animal physiology and anatomy that has formed the basis of much of what we know about functional anatomy and physiology in noncaptive, nonagricultural species. The second approach is the a posteriori *opportunistic approach* in which observations made during some form of unplanned event allow the development of a functional explanation about a connection between the event and an organism's response.

*Comparative approach*—This approach uses comparisons between the responses of similar organisms in similar regions when exposed to different sound fields. Comparison provides the means by which an effect of sound may be measured against some form of control treatment. The control may be some measure of an organism's behavior or physiology before sound exposure or for the same species in a similar, but quieter or noisier, environment. In such studies the dose of sound is uncontrolled and the response variables being measured are usually unplanned and detected post hoc from a range of measurements because there is normally no a priori hypothesis about the exact nature of the response to sound. Often, some form of multivariate statistical method (e.g., Bayesian techniques) is used to separate the signal in the data from noise associated with effects from uncontrolled variables.[7]

With the development of offshore industries that are increasingly regulated to limit the sound they produce, protocols are being developed to measure the impacts of these developments on some marine organisms. The required monitoring can often amount to studies conducted over many years and they may include several components:

1. Baseline assessment: documenting the state of the organisms of concern before the introduction of anthropogenic sound.
2. Impact monitoring: documenting any change in the state of organisms during the period when anthropogenic sound is produced.
3. Post-effects monitoring: documenting the return of the organisms to their original state after the period of anthropogenic sound production.

Variations on this approach include the capacity to compare the state of marine organisms in similar, and possibly contiguous, undisturbed and disturbed habitats simultaneously. In this case the "state" of organisms could include changes of behavior, physiology, social structure, or population density and population size. Ultimately, however, population size is likely to represent the end point of an accumulation of effects that result from acoustic and other stresses because this will reflect changes of fitness in individuals that accumulate at the population level to affect survival and/or reproduction. This means that measurements may have to be made over time scales of many years for species that have long generation times. Short-term changes in behavior, physiology, or social structure can be used as proxies for potentially significant (in terms of population trajectory) effects of acoustic stress. However, NRC (2005) points out the dearth of evidence relating repeated short-term changes and effects on growth, survival, and reproduction.

The following types of comparisons can be made:

a) Comparison across species and populations.

*[7] Uncontrolled or confounding variables are those factors that are not of direct interest, but cannot be considered to be the same in the control treatment and all experimental treatments. It is important to measure uncontrolled variables that are likely to have an effect on the variable(s) of interest.*

b) Comparison across habitats, locations, and time.
c) Comparison before and after sound exposure.
d) Comparison between pristine and noisy environments (and grades in between).
e) Comparison among treatments (e.g., pile driving, seismic, sonar, shipping sound).
f) Quieting as a treatment.

The IQOE will use opportunities to conduct studies on the effects of marine noise around the following sites:

1. Noisy and quiet environments

   Comparing animal behavior, abundance, and productivity between noisy and quiet environments reflects difficulties associated with attempting to ensure that the differences in the sites being compared are predominantly related to the soundscape. No two environments are identical and the differences in the soundscape may be small compared with other, unmeasured differences. However, research sites should be chosen carefully by the IQOE so that it is possible to compare the responses of animals across different soundscapes. This could be achieved using cross-sectional sampling of animals from resident populations within the locations being compared and longitudinally using the same individuals if they migrate among the contrasting acoustic habitats. Another opportunity occurs when sound exposure will move from one of the sites to another, with sufficient time to monitor both sites before and after the move.

2. Marine pile driving

   Offshore developments involving wind farms will result in pile driving on an unprecedented scale within some coastal regions. The effects of pile driving on marine life are poorly understood but, mainly as a result of the needs for industry to comply with regulation, research will be undertaken to examine the degree to which construction operations are compliant and to assess any effects on marine species. These research efforts would benefit from being included within the IQOE study design.

3. Seismic exploration

   The oil and gas industry has already done much to advance knowledge about the effects of sound on marine life through the direct sponsorship of research through its Joint Industry Program (http://www.soundandmarinelife.org/). The IQOE will continue to undertake these kinds of studies of the effects of seismic survey sound on marine life. This will be conducted in collaboration with the oil and gas industry (see Theme 4). However, there are also important opportunities to undertake research in association with academic scientists undertaking seismic surveys for geophysical studies.

4. Shipping

   The IQOE will also examine the effects of the propulsion sound from ships, which is one of the most pervasive sources of anthropogenic sound. The approaches used will capitalize on the highly constrained nature of shipping lanes involving pinch points at which ship sound is likely to be greatest and the use of gradients in sound levels away from shipping lanes. Many of the most useful locations are easily defined, but circumstances will exist where habitat is shadowed from the acoustic effects of predictable ship tracks. Some of these shadow regions will be identified as outputs from the soundscape modeling described under Theme 1, but examples already exist of changes in shipping lanes that provide an opportunity for a natural experiment on the effects of sound from shipping on marine life. Shipping lanes were moved out of the Santa Barbara Channel off California to reduce the effects of local air pollution from shipping, changing noise levels significantly (McKenna et al., 2012). If future changes like this were known in advance, they would provide opportunities for observing the state of marine organisms before and after the change.

5. Explosions

   Explosions associated with disposal of unexploded ordnance, decommissioning of unwanted infrastructure, and navy exercises are responsible for high-amplitude sounds of short duration. In some areas, especially areas where much historical ammunition can be found—such as the Baltic and North seas—these activities could contribute significantly to sound budgets. A study in the Dutch North Sea concluded that the contribution from explosions to the annually averaged ambient sound in that area was comparable to that from pile driving (Ainslie et al., 2009).

6. Unusual events

The effects of sound on marine life have been brought to public attention mainly because of the unusual and extreme response of some species of beaked whales to military sonar (Cox et al., 2006). Indeed, much of the current knowledge of the effects of noise on marine mammals comes from behavioral response studies (or controlled exposure experiments) conducted on behalf of the U.S. Navy to help resolve this problem. These types of studies will mainly be dealt with in the following section, but there remains considerable interest in the occurrence of unusual events, especially the stranding of cetaceans, in relation to offshore industrial activities. The IQOE will undertake analyses, where appropriate, of the circumstances under which unusual events have happened as a way of potentially identifying evidence for causes and effects in relation to anthropogenic noise.

*Opportunistic approach*—The opportunistic approach to gathering experimental data is the most extreme form of unplanned experimental design. Often the data have been collected before any research question has been developed, and there is a need in these circumstances to rely on post hoc statistical analyses to examine relationships between the responses of organisms and sound levels. In many circumstances, this will involve the use of statistical models to help partition the variance in the states or responses of organisms to particular causes. Often, Bayesian statistics can be used in this context.

The IQOE will improve the strength of opportunistic monitoring studies by establishing common protocols for data collection that could allow comparison across studies at different times with different stressors in the same site or at different sites with different natural and anthropogenic stressors. The IQOE is based on the idea that, rather than introducing additional sound and observing the effects of this introduced sound, there is a need to examine the responses of organisms to quieting. Comparative and semi-unplanned approaches provide an opportunity to make progress with this ambition.

## 4.4 Effects of changes in chronic noise

***Key questions***

- How can noise be observed over time to create a biologically meaningful measure of chronic noise?
- What are the effects of prolonged increases or decreases of noise on the physiology and behavior of key species?

The first question will be influenced by the results of Theme 1. The second question will require the IQOE to develop recommendations for long-term monitoring of the effects of chronic noise on marine organisms, probably in conjunction with long-term measurements of ocean soundscapes. This will be a "legacy activity" of the IQOE, which will hopefully extend far beyond the life of the project.

***Research approach***

A key goal of the IQOE will be to explore the effects on marine life of both increasing and decreasing sound, using independent controls. Although experiments in which sound exposure is controlled will be much more constrained in their extent and generality than opportunistic studies, the establishment of planned experiments will complement the more opportunistic comparative and semicontrolled approach described above.

Although large-scale manipulations (up to ocean-basin scale) will be important, such as moving shipping lanes, there will be an important trade-off between the spatial and temporal scales at which experiments take place and the feasibility of those experiments (Figure 4.5). Opportunities where the sound exposure can be changed over a 5- to 10-year period need to be identified. At present, the establishment of many marine reserves presents an opportunity to establish the capability to measure biological changes associated with changing levels of sound.

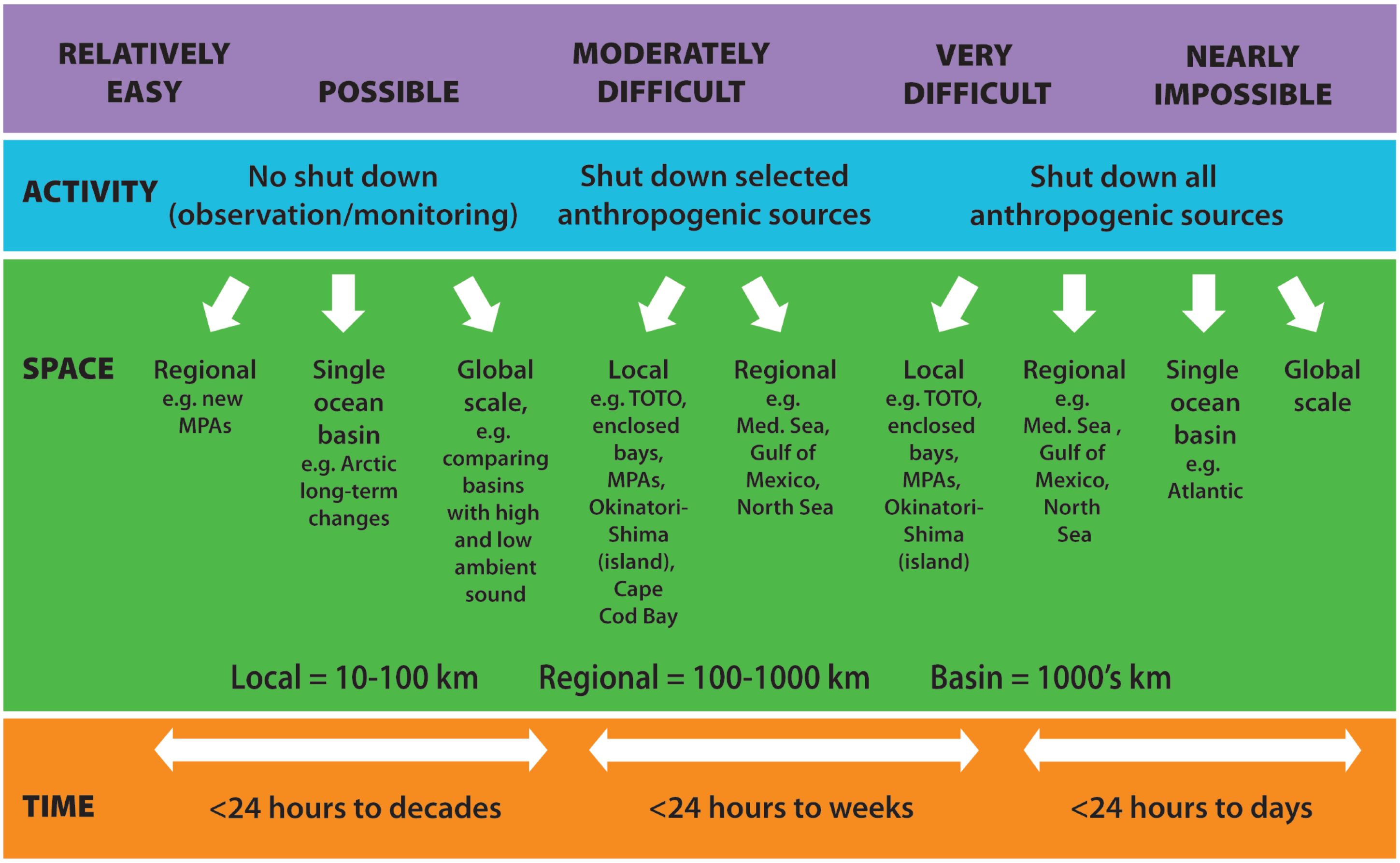


**Figure 4.5.** *Matrix of quieting feasibility. The difficulty and financial cost of a shutdown of noise sources increases from left to right in the matrix. The feasible time that a noise shutdown could be accomplished decreases from left to right (orange row). Different experimental activities (blue row) might be possible at different spatial scales (green row). The goal of the IQOE will be to conduct activities at many different scales. The relationship of the different temporal and spatial scales means that the most feasible approaches are likely to be several experiments carried out over long durations at small scales (i.e., toward the left of the diagram). Two roles that the IQOE will play will be (1) to help reduce the difficulty of experiments as one moves to the right in this diagram, and (2) to coordinate experiments of the type defined to the left of the diagram so that their data can be combined to deliver some of the benefits that will emerge if we were able to carry out experiments lying to the right of the diagram (from Boyd et al., 2011). Used with permission from the Oceanography Society.*

In ideal circumstances the most appropriate protocol will be to move sound sources to create contrasting (increased and decreased) sound conditions, and a key element to make this approach work will be to have enough advance notice (up to five years) to establish baseline observations before changes are made for other reasons. In the previous section, we also described a similar situation with opportunities associated with the introduction of sound because industry is expanding into new areas. The proposal here is similar, but in this case the experimenter has control of the sources and the study will be designed to detect effects of a shift from a noisy to a quiet environment and vice versa.

Long-term experimental studies are essential; short (weekly to monthly) studies are unlikely to capture the vital life-history effects except in short-lived species with rapid turnover, and they are often not the main focus of concern. The observations should include population counts and survival for short-lived species, and at least reproductive cycles for longer-lived species. In general, experiments should also include measurements of ecosystem covariates.

Experiments should not assume that a directional change in sound will produce proportional change in the response; nonlinear responses should be expected and sampling should be designed to capture such responses.

*Design of experiments*—A large-scale, long-term (lasting from months to years) experiment is proposed. This experiment will test the hypothesis that changes in chronic sound levels have biologically significant effects on individual target species (see above). In this case, biological significance is defined by its meaning described in Figure 2.5 and the related text.

To achieve the experimental controls, chronic sound conditions will be experimentally changed within defined study areas. Each area should ideally contain three subsites, one in which the exposure is increased, one in which it is decreased, and a third in which the level remains relatively unchanged (Figure 4.6).

Within each site, a targeted set of observations will be made and models will be constructed to quantify treatment variables (chronic background sound levels), response variables (to individual species and ecosystem dynamics), and potentially confounding variables (physical and biological oceanographic conditions). Although it is likely to be introduced initially at a regional or local scale because of the practicalities involved, this design could be used as a blueprint for an ocean-scale experiment.

*Predicting outcomes*—Although we have identified a general hypothesis to test, careful consideration will need to be given to developing a framework to predict outcomes of manipulations and the capacity to do this will have a strong influence on the location, species, and general situation chosen for an experiment. The general assumption underlying the design of IQOE experiments is that reducing sound will cause improvement in vital rates because sound as an external stressor is expected to have negative consequences for marine life. However, we should also consider the following factors:

1. How do animals use background sound, and have they become acclimated to higher sound levels or even experienced selection to sustain high performance under those conditions? Under these circumstances, it is possible that removing sound will lead to negative consequences.
2. Sound may alter predator–prey interactions. Changes in sound could have nonlinear consequences for community structure because even small changes in competitive interactions could have large effects on the dynamics in marine ecosystems. The same applies to predator–prey interactions.

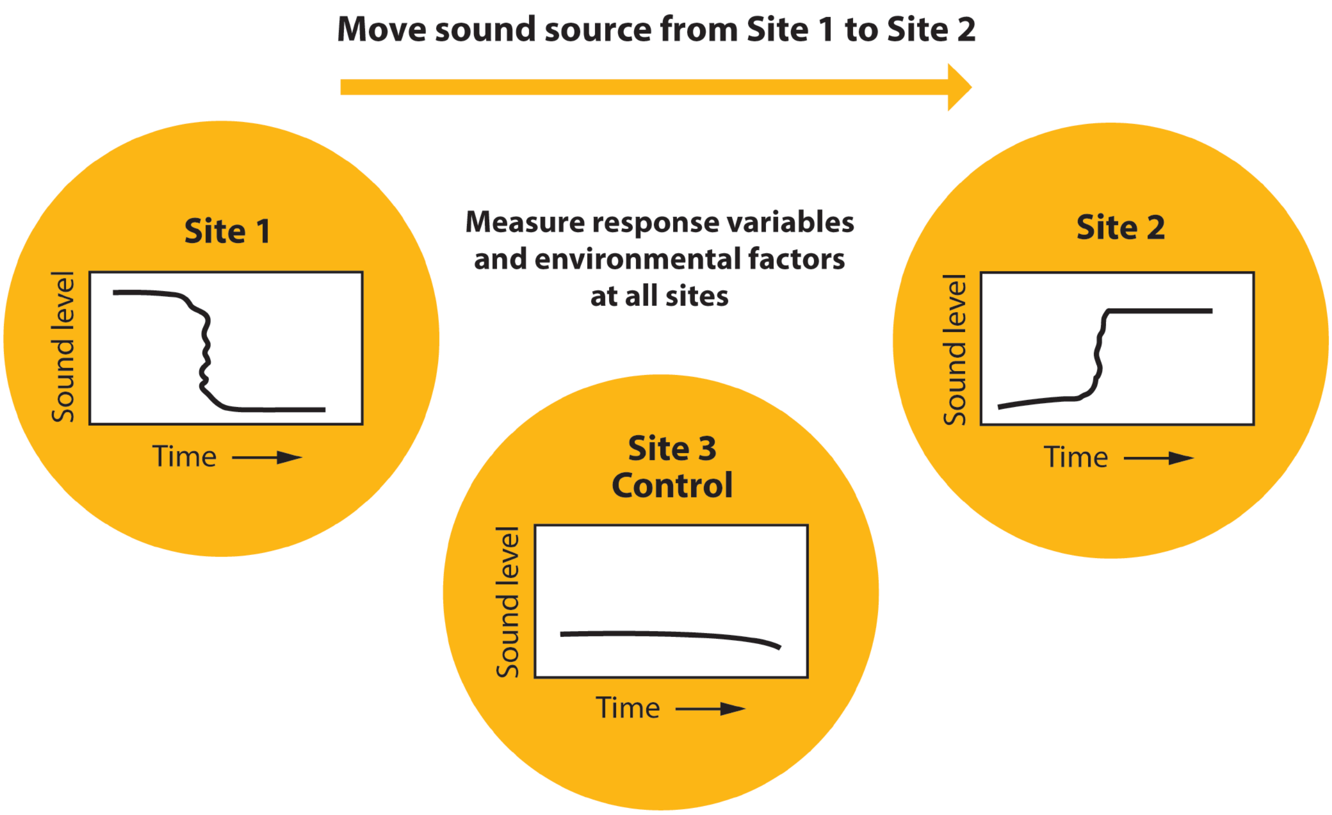


**Figure 4.6.** *Experimental design involving three locations. The time scales shown here will depend on the location and circumstances, and especially on the variance within the measured response variables, but they would normally require a minimum of two years, one year before a sound source was moved and one year after. Alternative, and simpler, approaches to this experimental design would be to compare loud and quiet areas or to measure effects over time in relation to changes in the levels of sound in small localized areas.*

The outputs from Theme 1 on Ocean Soundscapes will be important as inputs to this element of the IQOE. However, biological models of the system being studied will need to be developed in advance to predict the effects of experiments. The exact nature of these models will depend on the circumstances, but they could include population dynamics models or end-to-end ecosystem models. However, whatever model is chosen will need to be validated in advance of the experiments.

*Study species*—Ideally, study species should include a range of taxa—including invertebrates, fish, and mammals—each of which will provide different challenges to study. Organisms could be divided into categories by the role of sound in their lives, and their ability to hear and produce sound at frequencies of most interest. For example, if our focus is low-frequency sound, this defines the types of focal taxa as those with sensitivity to those frequencies.

The criteria for selecting species for inclusion in experiments might include the following:

- High sensitivity of the species to sound.
- Resident individuals should be preferred over migratory species and individuals.
- There should ideally be a high level of background knowledge of the species, and even individuals, if long-lived species are involved. For example, some individual whales are known by marking patterns and have been monitored over years.
- The species is important in the ecosystem, or is commercially important, or it has some specific significance to the stakeholder community.
- The species needs to be accessible, and measuring responses must be feasible. It will also be important to distinguish among treatment, confounding, and response variables.

The species selected may be different from those selected as target species for the studies on hearing capabilities, but there would be obvious benefits to using the same species.

Given these constraints, there are relatively few species that will fit all of these criteria. In particular, pinnipeds (Figure 4.7), because of their size and propensity to return predictably to breeding colonies, and some long-lived resident fish species within reef habitats, would be appropriate candidates.

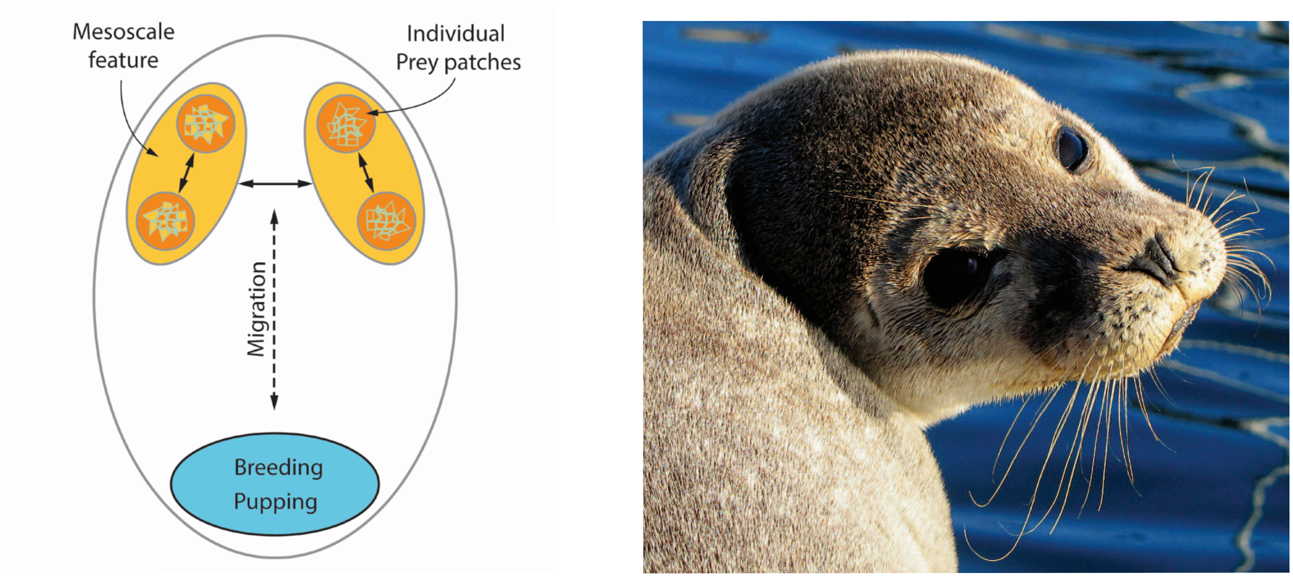


**Figure 4.7.** *Pinnipeds are likely to be appropriate for experimental studies. They are large enough to carry instruments, have predictable migration routes to and from predictable feeding locations, and return to specific locations on land, making individuals and populations feasible to monitor. They are also often a component of the marine fauna that carries specific legislation for their protection and management. Photo from Barbara Walsh (https://www.flickr.com/photos/barbarawalsh/5517303759/). Used under Creative Commons Attribution 2.0 (see https://creativecommons.org/licenses/by/2.0/legalcode).*

However, these types of experiment could be carried out at small spatial scales with species that are short-lived and accessible, perhaps using natural mesocosms in which species composition and ecosystem structure are well defined and possibly also controlled. This type of design also has the potential to include multiple species.

*Site selection*—The study sites will depend on the species being studied and the specific outcomes predicted for the experiment. A secondary feature will be the availability of baseline data from the site, to reduce uncertainty. Ideally, selected locations should have a long history of data collection on the species concerned. This type of criterion narrows the possibilities considerably.

Additional considerations include the following:

- Is there industrial activity in the area that could be used as the exposure and control? In some settings, it might be possible to shift the sound in a systematic way, but scientists need to work with industry to develop a consensus plan. For example, it may be possible to divert shipping for several years at a time, with enough advance notice, if this did not entail additional cost. In some cases, some shipping companies may decide to change their operating procedures for other reasons, affecting the routes used by its ships.
- Can the studies be replicated? If there were multiple independent sites (e.g., separate seal colonies) that could be monitored over a long period of time, this would provide an opportunity for replication. The choice of sites could lead to the development of different exposure scenarios for each site, for example, (1) increased sound, (2) decreased sound, and (3) no change in sound levels.

***Variables to be measured***

**1. Dose or treatment variables**
Measurement standards will be developed across different regions and species to make it possible to extrapolate beyond individual study sites and to determine global implications.

The most important dose or treatment variable is the sound received by the study animals (Boyd et al., 2008). Ideally, this should be measured directly from an instrument placed on or near the experimental animals, but also could be modeled based on information from the sound field (Theme 1).

**2. Response variables**
For each dose, the experiment will include defined response variables. Responses will be measured at different levels of the PCAD model (Figure 2.5), depending on the targeted organisms, for example, for short- versus long-lived species. With short-lived species, research will focus on vital rates as much as possible. For other species, it will be necessary to measure parameters that will allow estimation of vital rates. Individuals or species that leave the area and others that recolonize can also be measured by how they change their migration routes in relation to the sound sources. A combination of tracking and survey techniques may be applied, including mark-recapture studies and tracking of a subset of individuals. Tracking a subset of individuals over the observational period could also be used to study habituation and sensitivity.

**3. Confounding variables**
Confounding variables are those that can affect the responses to a specific dose or treatment in an experiment in a way that makes it hard to understand the results, particularly if the confounding variables are not measured. Some examples of confounding variables include ocean currents, temperature, salinity, chlorophyll, depth, bottom types, turbidity, and ice cover.

By using variation in the background sound levels, including intermittent noisy and quiet periods, it is possible to examine responses to a broad range of sound levels and types (e.g., chronic or acute conditions). This is as much about responses to quiet conditions as about those to the noisy conditions. Statistical models applied to these data can then be used to predict the effects of reduction in noise. An important goal of this element of the IQOE is to enable studies to identify areas where anthropogenic sound is already having deleterious effects. In such cases, quieting should have a beneficial effect. The duration of quieting windows should be carefully selected to be long enough to allow animals exposed chronically for years to return to a pre-exposure baseline.

## 4.5 Summary

Theme 2 aims to be the main driver for developing a deeper understanding of the connection between soundscapes and animal responses to the soundscapes. Therefore, it is important that considerable effort is committed to the tasks set out here.

When complete, these tasks should deliver representative dose–response functions relating the effects of anthropogenic sound for key species. Although, ideally, these should be in the form of classical dose–response curves, it is much more likely that they will amount to a mixture of these types of precise functional relationships between animal responses and sound levels and heuristic assessments of the effects of sound at various levels from behavioral response to effects on populations. These types of assessments are most likely to constitute a body of knowledge that, through appropriate combination with risk analysis (see Section 6 and Figure 6.3), will meet the needs of managers and decision-makers. Given the current poor state of knowledge, these assessments will represent a major step forward and, when combined with the outcomes of Theme 1 on Ocean Soundscapes, will also form the basis for making predictions about the potential effects of future changes in anthropogenic sound in the ocean.

# Chapter 5
# Theme 3: Observations of Sound in the Ocean

## 5.1 Introduction

Sound in the ocean is challenging, both to detect and to visualize. This problem is one that requires measurements in many dimensions: three spatial dimensions, plus time and acoustic characteristics, which might be considered as adding three additional dimensions—amplitude, frequency, and variability over time. The process of measuring ocean soundscapes (see Theme 1) is concerned with characterizing these dimensions to form a coherent picture. In Theme 3, we address the requirements of the instruments and observing systems needed to provide the raw data to allow the measurement of soundscapes at a very wide range of spatial and temporal scales. The theme also addresses the need to observe sound fields from the perspective of the marine life that may be affected by sound. Being able to observe the sounds that organisms are exposed to, and that they can hear, has been identified as one of the most critical first steps toward being able to measure the effects of sound on organisms (Boyd et al., 2008).

Only limited data are available on ocean soundscapes. Information on long-term changes in ocean sound levels, whether anthropogenic or natural in origin, is available at only a few locations in the world ocean, for a limited period. Measurements of underwater sound also provide data that can be used to track, count, and study the behavior of vocalizing marine mammals and fish, which can be used to help determine the effects of anthropogenic sound on marine life. Finally, active acoustic measurements, using instruments such as high-frequency scientific echo sounders or low-frequency ocean waveguide remote sensing (Makris et al., 2006), can provide information on aspects of the ocean environment, such as the density and distribution of marine life, especially within the water column.

In recent years, there has been a strong emphasis on the development of ocean observation systems (Kite-Powell, 2009). System development has been enabled partly by increasing technological capability, but also by recognition of the need for new data about the ocean, that sometimes need to be delivered in real time, as in tsunami warning systems. These requirements have driven innovation and it is likely that the need for observation systems and their capabilities will increase greatly in the next decade. Traditional ocean observatories using moored systems of sensors are being augmented by mobile sensors on floats (Roemmich et al., 2009), autonomous underwater vehicles (Nicholls et al., 2008), gliders (Johnson et al., 2009), and even instruments carried by marine mammals (Grist et al., 2011). Acoustic observation has not, in general, been a part of many of these systems and, when present, it is usually recording at very low acoustic frequencies that may be of greatest interest for observing seismic events or other physical changes, such as sea ice breakup, but is of less concern in frequencies that are important to most marine organisms.

## 5.2 Acoustic observation networks

Wherever possible, acoustic observations need to be included in ocean observing systems designed for other observations. This approach will contribute both to providing the information required to characterize the global ocean soundscape and make use of current and future infrastructure with minimum additional cost.

Hydrophone systems are already deployed for recording sound in the ocean, and many of these are listed in Appendix II. Other observing systems have been deployed for specific oceanographic, biological, chemical, or other environmental purposes, but have not included ocean acoustic sensors. One key benefit of integrating acoustic capabilities into such systems is that they would acquire diverse oceanographic and atmospheric data concurrent with the acoustical signals. These ancillary environmental data may be essential in determining the relationship between sound, the ecology of target organisms, and the environment. Some systems under development are cabled observatories, such as the U.S. Ocean Observatories Initiative, and offer unique platforms with power, timekeeping, and communications capabilities, thus providing opportunities for acoustical instrumentation. The IQOE has begun to identify and catalog existing and planned acoustical observation systems (see Appendix II). These systems have been described and tabulated according to several important criteria. The aims of this effort were to show what systems are available to address specific IQOE questions and to identify new acoustical capabilities that need to be developed for IQOE studies.

The remainder of this chapter places the IQOE into the context of the larger ocean observing systems; addresses the existing observation systems that either directly support acoustical measurements or could be configured to do so; suggests some examples of new technologies that would augment existing acoustical measurement capabilities; and recommends investigating the incorporation of acoustic measurements into ocean observation systems and their data management processes, either archived from prior monitoring activities, or collected by contemporary or planned regulatory activities. Finally, the theme addresses the issues of standardization of data in quality, calibrations, formats, and management to enable the comparison of results among international collaborators.

## 5.3 Acoustics and global and regional ocean observing systems

The IQOE cannot, and does not need to, unilaterally deploy global ocean observing systems because of the resources, experience, and effort already expended in establishing and operating global and regional ocean observing systems (OOSs). Available ocean observing systems already include a wide range of observing technologies, from satellite observations of a variety of oceanic variables (e.g., surface height and temperature, wind, ice coverage, and chlorophyll-a concentrations) to standard National Oceanic and Atmospheric Administration (NOAA) weather buoys and some Argo floats providing upper ocean sound profiles and some even featuring acoustic rain gauges.

As the IQOE evolves, it needs to evaluate the relevance of ancillary data from readily available OOSs and ensure the continuous accessibility of such data throughout the project. Time-synchronized multivariate sensing systems will be increasingly important as attention focuses on interpreting the potential ecological impacts of sound. Consequently, the application and integration of OOSs as contributors to the IQOE monitoring and experimental efforts is preferred over solely acoustic measurements. However, the type and nature of these ancillary data streams depend on the specific question and the environment in which measurements are made. Indeed, information and data missing from existing systems, but essential for addressing IQOE science questions, will require deployment of additional instrumentation. Some of these deployments will probably transition into operational components of OOSs.

Experience and technologies to promote good data management and communication (DMAC) have grown out of the OOSs. The IQOE will need to take advantage of DMAC technology, and begin a dialog with observing organizations to help incorporate acoustical data streams within OOSs, where possible.

The ocean observing systems include within their mandate educational and public outreach efforts. These efforts would naturally extend to any acoustical activities related to these systems (see Chapter 7).

## 5.4 Integration within existing systems

Most or all of the envisioned IQOE monitoring and experimental efforts should use data from existing capabilities or promote the integration of acoustics into existing observing systems. An early objective of the IQOE will be to complete an initial draft of what is envisioned as a continually updated survey of the known systems (included in Appendix II and online at http://www.scor-int.org/IQOE/Appendix II.pdf). The survey matrix will be available for public contributions on the IQOE Web site and related to a global map showing locations of existing acoustic observing systems (an incomplete example is shown in Figure 5.1).

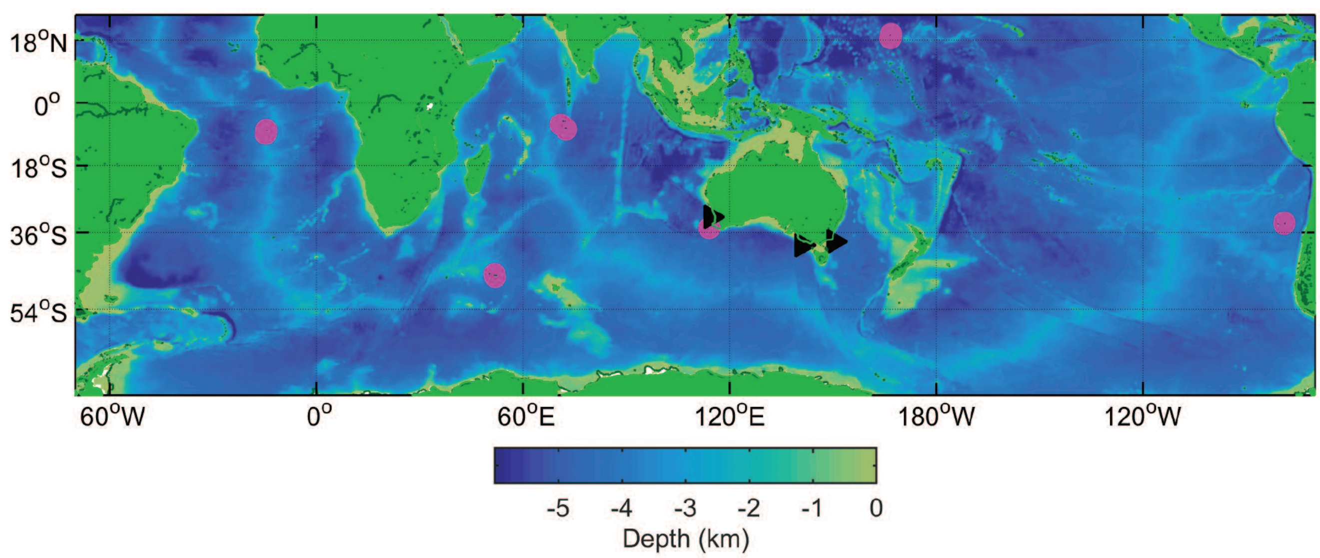


**Figure 5.1.** *Comprehensive Test Ban Treaty Organization (CTBTO) (magenta circles; see also Figure 5.2) and the regional Australian hydrophone facilities (black triangles) with ocean bathymetry derived from the Smith-Sandwell atlas (Smith and Sandwell, 1997). Each CTBTO receiver consists of a triplet of hydrophones to make it possible to determine the direction of acoustic signals. Data are recorded, processed, and transmitted to shore in real time from these arrays. From Dushaw et al. (2010). Permission to reuse figure granted by authors.*

Appendix II categorizes observing systems as cabled arrays (e.g., fiber-optic systems), remotely deployed archival systems (e.g., bottom-mounted recorders), and mobile systems (e.g., drifting buoys, gliders, animal-borne instruments). Each system was assessed relative to

- geographic location;
- whether acoustics is a current operational capability;
- various system characteristics;
- the inclusion and type of ancillary (nonacoustic) data;
- relative accessibility of data from each system;
- potential integration with other systems;
- sponsoring entity;
- general societal benefit or product of each system; and
- installation duration and life expectancy.

The derivation of the system matrix in Appendix II according to these criteria was intended to provide a basis for system selection when the experimental/monitoring areas and objectives are chosen (e.g., in Theme 2). The anticipated process would be the consideration of specific experiments, each with its own time-space resolution and objectives.

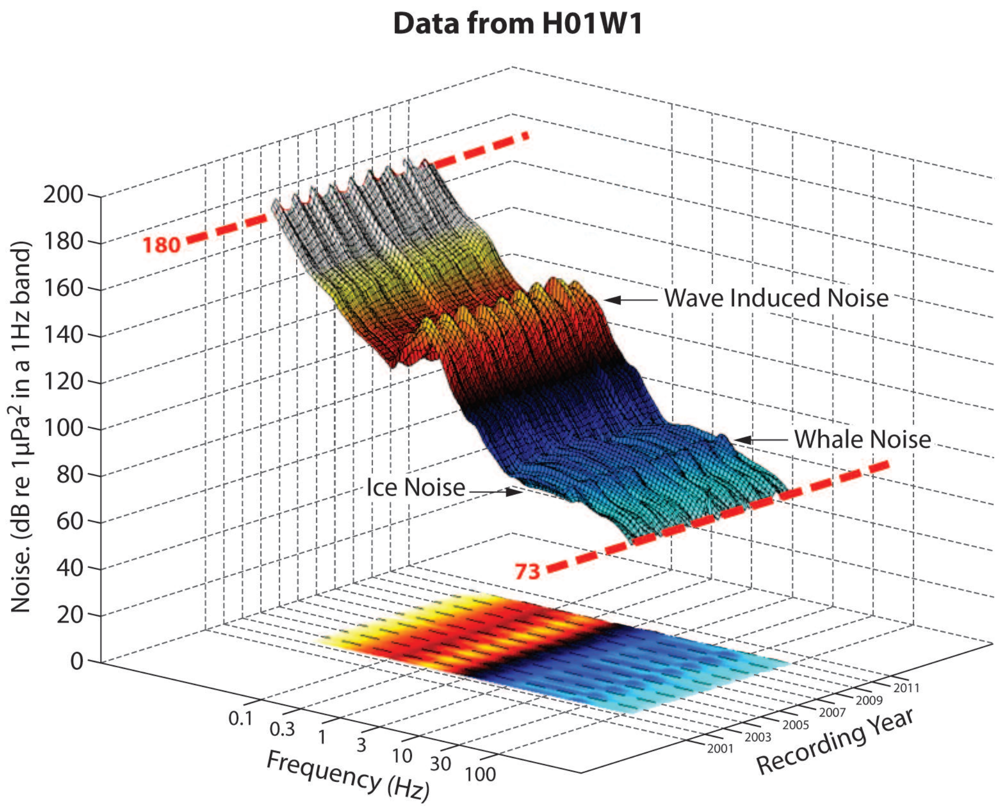


**Figure 5.2.** *Ambient sound spectral density level in relation to frequency through time recorded at one of the CTBTO sites in Western Australia (see Figure 5.1). The seasonal peaks at low frequencies are related to Antarctic ice breakup and at the higher frequencies these relate to seasonal calling by baleen whales. This is an example of the kind of depiction of the soundscape that could be achieved across many OOS sites. From Prior et al. (2012). Reproduced with permission from the Comprehensive Test Ban Treaty Organization.*

## 5.5 New systems designed for the IQOE

It should be possible to use existing passive acoustical technologies within existing and planned ocean observation systems. However, it appears unlikely that sufficient monitoring systems with passive acoustic capabilities exist in enough areas of the ocean to accomplish the broad and sustained monitoring objectives of the IQOE. There is a need to conduct a detailed assessment, probably through one or more workshops, of the observation capacity that is required to meet the objectives of the IQOE, and to assess the extent to which modification of current and planned capabilities in ocean observation are likely to fulfill these objectives.

Although it is preferable to use and improve on the capabilities of existing systems, there will be instances where integration of currently available sensors into existing systems will not be possible, or existing system nodes may not be located in the appropriate geographical area(s) targeted for program experiments. In such cases, the IQOE may need to establish dedicated monitoring. The development of technology that would enhance the information available from existing systems and sensors has been identified in six areas:

1. *Particle motion/vector sensors*—Research has shown that a majority of fish species studied are more sensitive to the particle motion component of sound than to the pressure component (Popper and Fay, 2011). The need to measure this parameter is important for providing the proper environmental context for fish in response to sound exposure.
2. *Portable system designed for the IQOE (single hydrophone)*—In areas where OOS networks do not have regional nodes or coverage, it will be necessary to provide small, inexpensive, portable systems designed to provide required acoustic, and where necessary, other measurements. Many of these are already being developed and are available, although they may not have all the essential characteristics required. These portable systems need to provide information relating to the survey of global ocean soundscapes and short-term experiments, and they need to be compatible in their sensitivity and the way in which data are presented. Such portable and inexpensive devices will encourage wider international participation in the IQOE.
3. *Modular hydrophones to assemble horizontal and vertical line arrays*—The ability to assemble modular arrays quickly and efficiently will enhance our capability to provide directional acoustic data to the global soundscape survey effort and short-term experiments.
4. *Data transmission technology*—The limited bandwidth of current satellite transmissions is often a bottleneck for the transfer of high-volume acoustic data. Developments in this area on the recording hardware, processing, or data transfer aspects would be beneficial to the IQOE effort.
5. *Acoustic backscatter sensors, echosounders, and acoustic waveguide remote sensing*—Existing OOS and satellite networks provide valuable information on physical ocean properties and primary productivity. Passive acoustic monitoring (PAM) provides information on the presence of vocalizing animals (mammals and fish). The development and incorporation of scientific echosounders (for example) into OOS networks would provide the capacity to measure zooplankton and fish distribution and concentration in the water column, and to study the predator–prey dynamics of an area, which is needed to provide proper context for interpreting the effect of changing sound levels on marine animals. NEPTUNE and VENUS already have active acoustics capabilities, but this is not a widespread capability across OOS networks.
6. *Compliance monitors*—A simple sound management tool might be needed to monitor and report the acoustic state of a vessel. This could provide real-time information of the ship's acoustic state via the Automatic Identification System (AIS), which indicates a ship's identity, position, course, and speed.

## 5.6 Extracting useful scientific information from data collected for regulations

So far, we have considered only scientific OOS networks, but there will be a need for observation systems that assess compliance with limits on the additional sound in the ocean from anthropogenic sources. The need for these systems is developing quickly in various jurisdictions. In Europe, this is a specific requirement of the Marine Strategy Framework Directive (MSFD, 2010). Some of these observation systems may be in place for short periods when industrial development is proceeding, but there may also be other networks operated by coastal nations to demonstrate national compliance with targets for sound production from human activities.

The IQOE could adopt two different approaches to building on this opportunity. One would involve the analysis of acoustic data obtained in the course of regulatory monitoring of industrial developments. Alternatively, as regulation of ocean acoustical pollution is initiated throughout the world, the associated monitoring systems could be sources of future datasets, and the IQOE has an opportunity to influence the design and placement of such systems.

***A survey of historical data to establish the nature of soundscapes of the past***

Trends of sound are considered in more detail under Theme 1, but it is recognized that the assessment of trends needs to link with observing systems. Time series of acoustical data have been collected at multiple locations in multiple regions over the past 50 years. Many of these datasets were generated by private industry, military, research institutions, and regulatory agencies for regulatory compliance, exploration, research, and targeted surveillance. Some of these data are proprietary or have national security classifications; whereas other datasets are openly available. For example, the U.S. Office of Naval Research (ONR) has supported the acquisition of acoustic data through its research programs, while the Naval Oceanographic Office (NAVOCEANO) has acquired extensive acoustic datasets through its survey efforts. However, these data are often not readily accessible to the scientific community because of either security restrictions or practical issues associated with processing and interpreting data recorded on various media and archived in a wide range of formats. Similar situations exist in other nations. At an early stage, the IQOE will undertake a comprehensive survey of historical data. This task will need to be undertaken by an IQOE group made up of providers and users of the data. A database will be established on the IQOE Web site to allow input of historical data, as well as new data (see the discussion of DMAC in Section 7.3). For these data to be useful, they must have been adequately calibrated, which may limit the amount of historical data that will be useful.

Historical data may not be in the format agreed upon by the IQOE, but targeted datasets could be reprocessed for contribution to the IQOE. The information resulting from the historical data survey and new data acquisition will provide information to the IQOE about historical soundscapes in areas of interest for comparison with the present and for validating contemporary acoustic models. Coordinating independent teams working on these problems simultaneously will help to provide cross-validation where it is not possible to validate using data.

***Sources of future data for the IQOE***

Government-mandated regulation of either radiated sound from individual sources or cumulative anthropogenic sound contribution in a targeted region will require monitoring instrumentation that may be a source of acoustic data for the IQOE. As an example, the U.S. National Marine Fisheries Service held a workshop to estimate a comprehensive sound budget for the ocean, with a special focus on the U.S. Exclusive Economic Zone, as part of the NOAA Cetsound project (NOAA, 2012). In the EU, the Marine Strategy Framework Directive (see Tasker et al., 2010) specifies that all EU member states monitor their marine environments to regulate the contribution of anthropogenic sound energy. This directive will require new monitoring systems throughout European waters. While the actual legally binding monitoring requirements are likely to be very narrow, the instruments being used to provide this information will have the capacity to collect considerable additional data about sound. Consequently, the IQOE should establish data-sharing agreements that permit continuous delivery of these data to an IQOE data assembly center. An important task of the IQOE will be to involve data generators and managers globally to take advantage of the widest range of data available.

Since these kinds of data will be formatted primarily to meet the needs of regulatory agencies, it will be critical for the IQOE to coordinate with the agencies as early as possible to influence the data formats, and subsequently to devise any necessary reformatting procedures to transform the available data products into the IQOE formats. Technical contacts representing the IQOE will need to be appointed to interface with regulatory agencies, and the details of the data interface and any subsequent data reformatting may profit from attention as a subtopic at an IQOE technical workshop (if the issue arises early in the IQOE). We propose that a standing committee on data management should emerge from this workshop. Although these examples are specific to the United States and Europe, the IQOE should investigate whether similar opportunities or initiatives exist in other regions of the world and ensure effective liaison between those initiatives and the IQOE. An important activity of the IQOE will be to work with navies and all offshore engineering industries, including those in oil and gas exploration and production, wind-farm deployment and operation, bridge and tunnel construction, offshore mining, etc., for access to proprietary and classified data in a way that will advance the science without compromising the interests of those providing the data.

## 5.7 Data collection (including standardization), quality control, analysis, reporting, management, and accessibility

Of similar importance to synoptic measurements is the use of standards and the application of a systematic and standardized data management structure. Information and potentially important trends and observations are likely to be lost or unused unless an explicit strategy is implemented for data archiving, analysis, and sharing. Data acquisition and reporting standards are an important part of data management, as is the development of data sharing agreements that ensure the rights of individual data originators. As with ancillary data measurements, data management strategies require considerable deliberation and planning, and will vary depending on the systems employed and questions asked.

We recommend that a technology workshop be convened to define standards that will lead to a proposal for the global soundscape project. This workshop will include representatives from the major observing systems but will necessarily follow specification by IQOE acousticians regarding experimental design. These specifications will strive to provide data acquisition and management standards and protocols for (at least) the following variables:

- Bandwidth
- Bits, resolution
- Sensitivity
- Units
- Sample rate
- Data format
- Analysis methods
- Calibration
- Metadata and data accessibility

The workshop is necessary to (1) enable agreement on terminology, (2) enable agreement among the acousticians on the standards for data and metadata, and (3) compile the acoustical data available from individual ocean observing systems.

## 5.8 Biological observing systems

The development of biological components of the OOSs have lagged behind the physical components, but the biological components were highlighted during OceanObs'09 (e.g., Gunn et al., 2010). An important class of acoustical system consists of those that employ passive acoustics for monitoring marine life, including distribution, abundance, and behavior (Mellinger et al. 2007; Van Parijs et al. 2009; André et al., 2011). Satellite observations of some biological variables are also available.

Biological observations collected for the IQOE may demonstrate their long-term importance and consequently transition to operational status and become elements of ocean observing systems. Combining biological observation with observations of sound will have two specific advantages. First, this will make it possible to develop experiments that relate the general bioscape (i.e., the acoustically determined distribution and abundance of components of marine communities, most probably in pelagic habitats) to other ocean sound variations. This will enable some options for developing *effects studies* as described under Theme 2.

Second, combining biological and acoustic measurements will enable identification, classification, and possible estimation of the abundance of organisms that are the sources of sound (Marques et al., 2009). Software to achieve such goals is in a fairly advanced state of development (Figure 5.3), but the IQOE will stimulate the development of open-source software for the automated identification, localization, and classification of biological sound sources from ocean observation platforms.

## 5.9 Synthesis and modeling: physical, biological, and acoustic

Modeling will be an essential component of the IQOE for predicting ocean sound levels across the globe, estimating acoustic propagation of sound over space and time, and assessing impacts of changing sound on animal populations. Theme 1 concerning ocean soundscapes and Theme 2 concerning the response of marine life to sound both require the application and further development of models of how sound travels in the ocean.

A three-input modeling approach will be needed to integrate the acoustic, biological, and oceanographic data necessary to relate sound to biological dynamics because the three separate datasets are interrelated when assessing the impacts of acoustic change at the population level of animal groups. There are currently no models that predict the effects of chronic sound on marine animals, and much will be learned by an ongoing review of models now used to predict impacts of acute acoustic exposures. The Population Consequences of Acoustic Disturbance (PCAD) model will be a major conceptual tool for the IQOE (see Figure 2.5), but other modeling approaches will also be encouraged and used.

Models used within the IQOE will help project scientists understand how soundscapes change over space and time, using measurements made worldwide. To develop the most appropriate models, more accurate characterization and measurement of sound sources (biological and anthropogenic) is needed. Calibrated historical data (e.g., decades of data from navies, data from industry, data resulting from regulatory requirements) will be valuable for validating models and testing model predictions. However, there will also be a need for high-quality bathymetric data and integration with regional oceanographic models to enable accurate predictions of the sound field in particular locations. Consequently, there is a need for the IQOE to take an active and leading role in the development and implementation of new acoustic models that better integrate or set parameters for fine-scale details derived from new data and oceanographic modeling. See Theme 1 for further discussion of modeling and model validation.

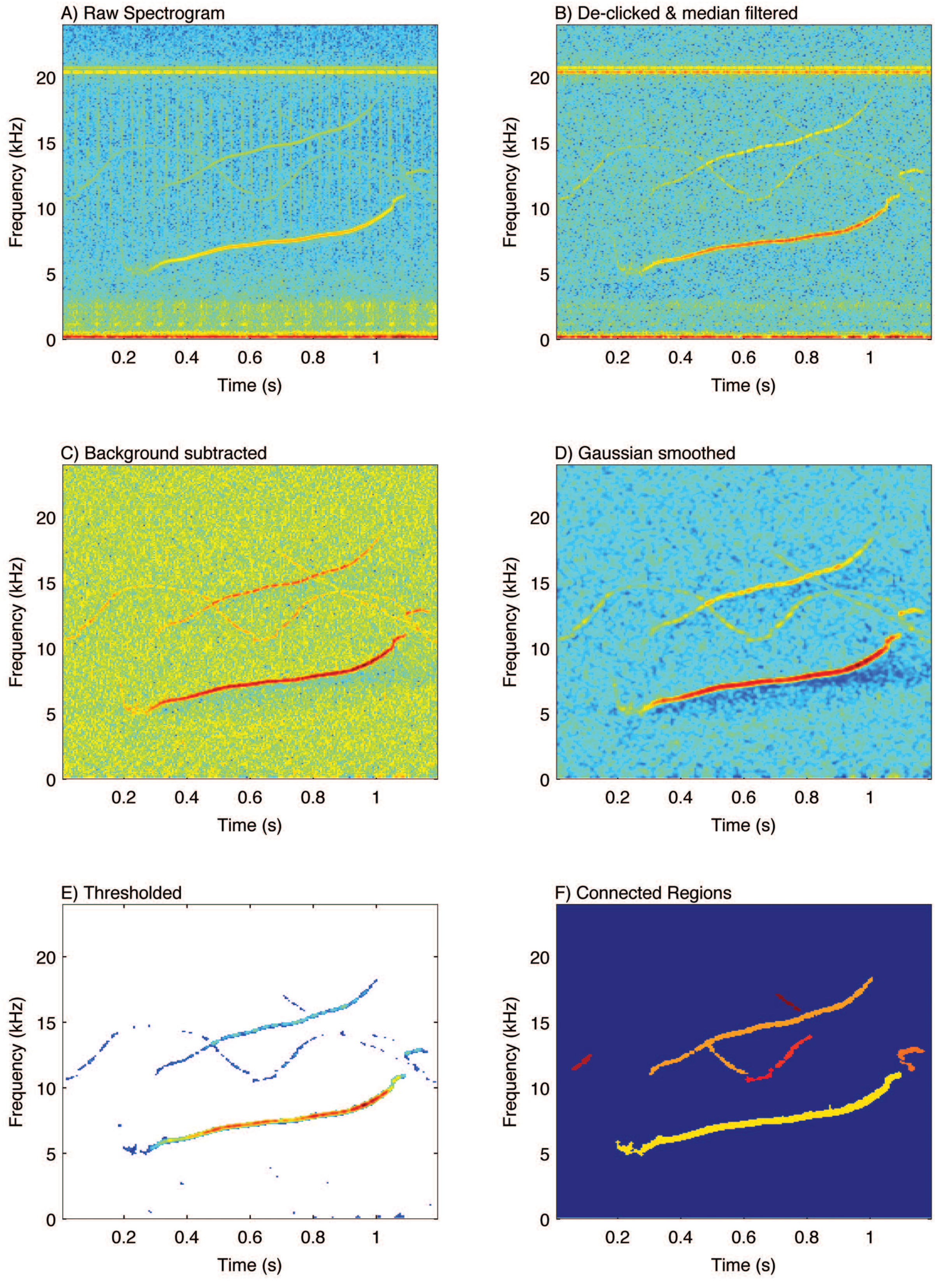


**Figure 5.3.** *Spectrogram of a typical dolphin whistle, showing the effects of the various processing stages of whistle contour extraction. This is typical of the processing carried out within whistle analysis software to enable identification of species. From Gillespie et al. (2013). Used with permission from the Acoustical Society of America, Copyright 2013.*

## 5.10 Recommendations

***Monitoring/experiments for the IQOE***

Five specific, though not mutually exclusive, types of monitoring or experimental efforts are recommended:

*1) International Year of the Quiet Ocean*

The International Year of the Quiet Ocean (IYQO) lies within the broader concepts of the IQOE, but there are opportunities to use a focused period of activity to make important progress. What is envisioned is a high-visibility international effort with coordinated observations around the globe over a short period to compare with modeling results. This yearlong activity would represent just the beginning of such coordinated observations and modeling. The intention is that this approach will produce a global map of soundscapes, and that these point measurements will inform subsequent models (see Theme 1). To establish a baseline of the soundscapes of the world's ocean basins, international coordination will be required to obtain comparable data in different locations. Ocean soundscape models are being developed through programs of U.S. agencies and others, and a workshop was held in the Netherlands in April 2014 to discuss progress on these modeling efforts (http://scor-int.org/IQOE/Leiden_Report.pdf). The data collection started in the IYQO will need to be continued to address the effects of seasonal, annual, and decadal environmental variability on ocean soundscapes.

*2) Long-term measurements of sound*

A high-priority effort for the IQOE should be the initiation of long-term monitoring of sound, particularly at low frequencies, over ocean-basin scales. Monitoring will also be required at a relevant vertical resolution because, while sound may travel considerable distances when the receiver is in the SOFAR channel, most biological receivers are not at that depth. The intent will be to focus in a sustained way on characterizing variability in overall sound, human contributions, and biological use of areas and possible impacts of anthropogenic sound. Low frequencies will be a particular focus because of the propagation of low frequencies over ocean basins and the likelihood that many of the animals that might respond to sound are those that use low-frequency sound (e.g., whales, fish). Observation systems are available in many likely study areas, but will probably need to be augmented for more complete coverage, particularly in abyssal areas of an ocean basin and within coastal regions where the patterns of sound transmission can be complex and difficult to predict with existing models. The Global Ocean Observing System (GOOS) is now engaging in identification of Essential Ocean Variables that would be monitored by GOOS into the future, and the IQOE will aim to provide input to this process as part of Theme 3.

*3) Observation efforts to support regional "experiments"*

We envision a geographically focused study with potentially short-term changes in the sound field. This study could include comparison of two similar habitats in an area of somewhat rapid change or contrasting anthropogenic activity, such as comparing the Gulf of Mexico with the Gulf of California. Such an experiment will occur over a regional spatial scale (e.g., tens to hundreds of kilometers) on weekly to decadal time scales, and will necessarily consider a broader frequency range than long-term measurements. It will consider a larger number of individuals of the target species and possibly also examine community-level effects.

This approach could include opportunistic studies such as those done in relation to the changes in shipping lanes around the California Channel Islands (see Theme 2), and could focus on areas of planned changes in shipping regulations, for example, the no-boat zone in San Juan Islands (before/during/after), and designation of Particularly Sensitive Areas (PSA) (subcommittee within IMO) involving rerouting of ships. The potential rerouting of shipping from Asia to the United States to pass farther south of the Aleutian Islands is a further opportunity. Another opportunity involves the presence of transient industrial noise, such as pile driving for the construction of wind farms. Other opportunities could exist on new gas platforms installed off Russia, in new leases in the Barents Sea, and in changes in maritime traffic in the Canary Islands area due to logistic and overload issues at large container-ship harbors in the Mediterranean Sea and Suez Canal area. The Suez Canal authority is developing a project to increase the depth of western channels of the Suez Canal from 48 ft. to 52 ft. This project is expected to affect traffic, some of which would have to be redirected temporarily along the west coast of Africa. The Las Palmas harbor in the Canary Islands can handle large container ships and thus it is expected that during these project periods, which may be repeated in the course of the IQOE project, a notable increase in traffic may occur and would be monitored by the PLOCAN observatory station and at the ESTOC site (see http://estoc.plocan.eu/en/).

Teilmann and Carstensen (2012) provide an example of how such opportunistic studies can be conducted. They monitored the acoustic activity of harbor porpoises before a wind farm was installed, during construction, and for a long period after construction. The observations demonstrated decreased acoustic activity (and presumably reduced presence of porpoises) during construction of the wind farm, but gradual reoccupation of the area by porpoises during the regular operation of the wind farm.

The IQOE will establish an appropriate mechanism for interacting with the organizations and agencies involved in observations. To this end, the IQOE will appoint and fund a representative to attend meetings and make the case for participation of the IQOE in observation activities.

*4) Arctic study comparison*

The increasing retreat of the Arctic ice cover is opening up that region to increases in human activity, which is expected to bring profound changes to the natural (but not quiet) soundscape. Because of expected climate changes there is a unique opportunity to observe the effects of increasing levels of anthropogenic noise in this region. The Northwest Passage may in this context provide a specific area of interest to monitor soundscape changes given the increased presence of passing ships. A challenge for the IQOE will be to design experiments that can distinguish between the effects of changes in sound levels from other environmental change, such as change in ice cover.

The ecological changes in response to a changing soundscape are not expected to occur instantaneously, but rather are expected to occur over at least the duration of the IQOE and probably decades into the future; therefore, in addition to programs of short-term autonomous measurements, this suggests that the IQOE press for a long-term monitoring effort.

*5) Antarctic study comparison*

Numerous observational efforts are also underway in the Antarctic using autonomous systems (Figure 5.4), and the IQOE should coordinate with these efforts. However, if we wish to develop a system for making long-term measurements of the background ocean ambient sound, then placing sound observatories under Antarctic ice sheets would enable the collection of data that is free of near-field interferences. Although technically challenging, both the Ross and Filchner ice shelves would be appropriate for this purpose and would "look" out into the South Atlantic and South Pacific oceans, respectively.

**Figure 5.4.** *The Perennial Acoustic Observatory in the Antarctic Ocean (PALAOA) continuously records the underwater soundscape near the ice shelf edge, 12 km from the German Neumayer-Station III. Photo: Thomas Steuer, Alfred-Wegener-Institut (see http://www.awi.de/fileadmin/user_upload/News/Press_Releases/2013/3._Quartal/Buckelwale_Ilse/2011Palaoa_TSteuer_p.jpg).*

# Chapter 6
# Theme 4: Industry and Regulation

## 6.1 Introduction

The societal response to concerns about the effects of underwater sound generated from human activities has been to introduce legislation and establish regulations to govern sound-generating activities. Although still at an early stage in development, mainly because of the limited evidence for effects of sound on marine life, the legislative frameworks currently in existence tend to give government policymakers the option to introduce highly precautionary regulations. This tendency toward caution is mainly the result of high scientific uncertainty. As examples, both Europe and the United States have these types of legislative frameworks.

The legislative basis for most U.S. regulation focuses on the protection and recovery of particular species (Hatch and Fristrup, 2009), whereas European Union legislation is focused mainly on reducing the introduction of sound energy into the water (Tasker et al., 2010). EU regulation also includes aspects of species protection, directed at listed species and at the protection of critical habitats, within the Habitats Directive. Under the U.S. Endangered Species Act (ESA), acoustic injury or disturbance of any listed marine species or population is considered when determining whether an activity will ”jeopardize” the existence of the species or population. The ESA also may consider whether human-generated sound will destroy or adversely modify habitats that are critical to the listed species. The U.S. Marine Mammal Protection Act (MMPA) prohibits “taking” marine mammals, where “take” is interpreted as to kill, injure, or harass individuals. The MMPA requires that human activities that could violate this prohibition, including harassment of marine mammals by sound, are subject to a permitting process. Exposure thresholds relevant to the MMPA have been established by the National Marine Fisheries Service of the U.S. National Oceanic and Atmospheric Administration (NOAA) to regulate potential impacts of sound on marine mammals. For whales exposed to sequences of pulsed sounds, the threshold at which harassment begins, as defined by regulators, is a received level at the animal of 160 dB re 1 Pa. For continuous sounds, the threshold is lower: 120 dB re 1 Pa. For seals and sea lions, the thresholds are 180 dB re 1 Pa and 160 dB re 1 Pa, respectively (NOAA, 2005; Hatch and Fristrup, 2009). These simple numerical thresholds imply zero response below the threshold and 100% response above the threshold. Moretti et al. (2014) used response data to develop more realistic, gradual dose–response functions for predicting impacts of sonar sounds on beaked whales (see Theme 2). The effectiveness of these types of regulatory approaches relative to the costs to human activities that produce sound in the ocean has been debated extensively and inconclusively.

The global commercial shipping fleet expanded from about 30,000 vessels (of about 85,000,000 gross metric tons) in 1950 to more than 85,000 vessels (about 525,000,000 gross metric tons) in 1998 (NRC, 2003). About 90 percent of world trade (in gross tonnage) depends on ship transport and, apart from declines during global economic downturns, the gross tonnage of goods transported by sea has steadily increased since the early 1970s. A theory has been proposed by Frisk (2012) that quantitatively links increasing low-frequency ambient noise levels to commercial shipping activity, which in turn, can be correlated with global economic trends (Figure 6.1).

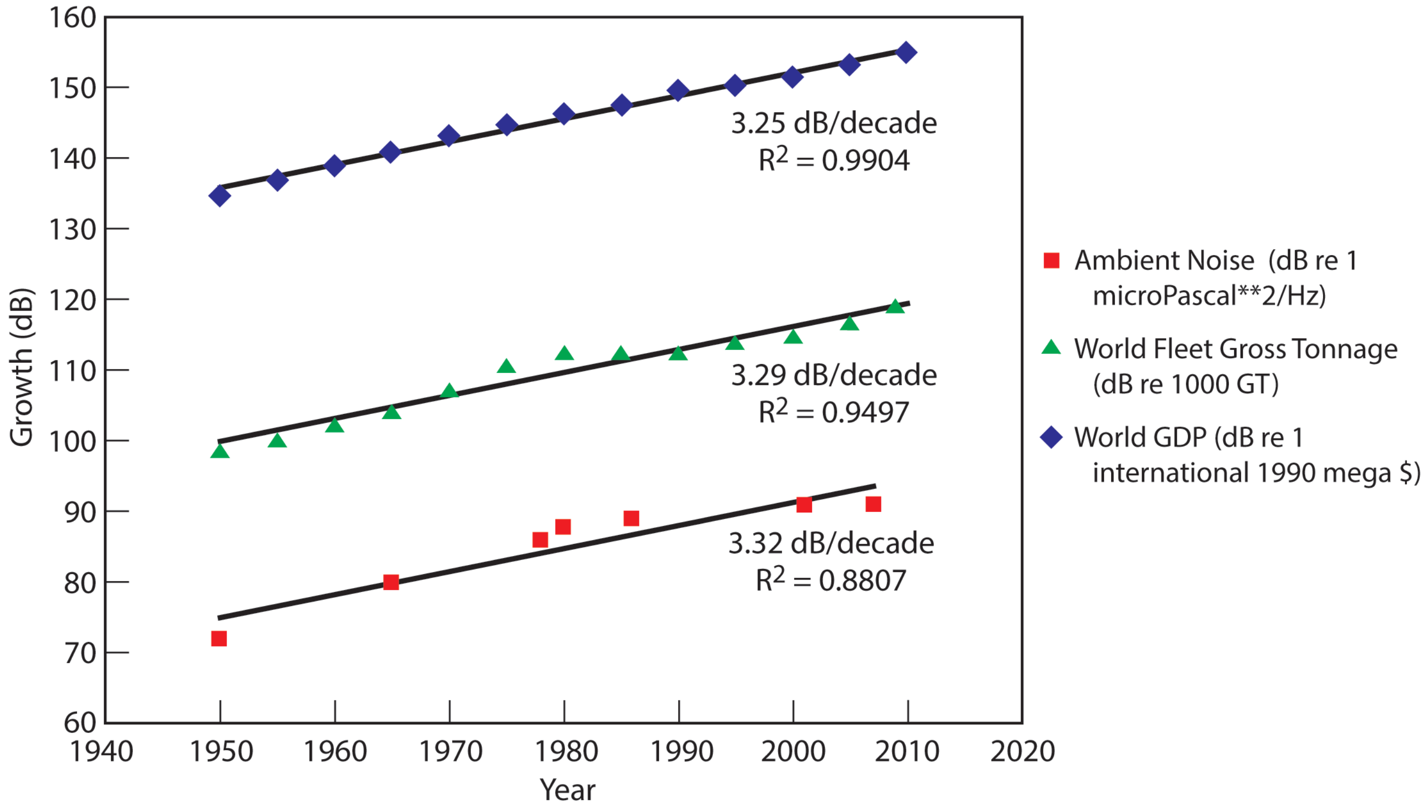


**Figure 6.1.** *Measurements of ambient noise levels, world fleet gross tonnage, and world gross domestic product are plotted as decibel (dB) quantities for the period 1950-2010. Linear fits to the data for all three quantities show similar slopes of 3.3 dB per decade with high goodness of fit ($R^2$) factors (Frisk, 2012). Used from Frisk, G.V. 2012. Noiseonomics: The relationship between ambient noise levels in the sea and global economic trends.* Nature Scientific Reports *2, Article number 437, doi:10.1038/srep00437, with permission from George V. Frisk, as allowed under the Creative Commons license.*

A continuing increase in shipping traffic is not certain because there could be an upper limit in the growth of ship transportation of goods brought about by (1) periods of slow or stagnant economic growth, as happened in the mid-1980s (Figure 6.1); (2) increased efficiency of the movement of goods; (3) reduced availability of raw materials or more efficient local sourcing of raw materials; and in the very long term (4) slower increases in demand because of leveling out of the global human population and especially the population of richer Northern Hemisphere nations. Nevertheless, all of these scenarios are uncertain, and it is possible that the recent growth of shipping will continue for the immediate future. Alternatively, technological improvements in engine and hull design could result in the sound produced by ships not increasing in proportion to either the number of ships or the tonnage of goods moved. This may be an explanation for the difference between the rapid increase in shipping since 2000 shown in Figure 6.1 and the decline in apparent shipping sound in the ocean shown in Figure 2.3 (Andrew et al., 2011). Theme 1 on Ocean Soundscapes will help resolve whether there is a relationship between low-frequency omnidirectional ambient sound and shipping.

Changes in ocean sound will also be caused by other key human activities, such as oil and gas exploration and other offshore engineering. The IQOE is aimed principally at resolving some of the critical scientific uncertainties associated with our understanding of how sound travels in the ocean from these kinds of human activities to organisms, and how organisms react, both individually and as populations. Only partial progress will be made during the IQOE, and considerable uncertainties will remain. It is important, therefore, that the IQOE has the capacity to maximize its effectiveness in the long term within the arenas of policy and regulation by rendering current approaches to regulating marine sound more effective. In other words, the IQOE needs to have a legacy that will be effective far beyond its completion.

This theme will develop the applied axis of the IQOE research activities to complement the more fundamental research of the other themes. Some of this theme's approach will include specific research that could provide the basis for more informed approaches to regulation, such as those used by NOAA for regulating effects on marine mammals (NOAA, 2005), but much of the work in this theme will involve weaving an applied thread through the activities defined in Themes 1, 2, and 3, and increasing the likelihood that the knowledge gained is used in future regulatory activity. Consequently, some of the activities mentioned in this theme refer to those in other themes.

Managers, industry representatives, and government scientists have been involved in IQOE planning from the start and were responsible for creation of this section of the Science Plan. The IQOE will continue to seek to involve managers, regulators, industry representatives, and environmental NGOs in planning for IQOE observations and research, most likely through a subcommittee of the IQOE Steering Committee.

## 6.2 Risk frameworks

### *General description of risk frameworks*

Exploitation of the ocean and its resources is a necessary part of human economic and social development. Continued expansion of the global human population, together with declines in the availability of basic raw materials, including energy resources, creates an imperative to continue to exploit ocean resources at least at current levels and probably much more in the future.

Therefore, industrial development will continue even in the face of increasing regulatory constraints. In these circumstances, it can be costly to wait until scientific knowledge catches up to help ensure that industry can move forward with a high degree of certainty that the options chosen for future development will not significantly decrease the sustainability of the ocean environment. Consequently, we need a framework within which progress can be made in a measured manner, while simultaneously minimizing risks to the environment and the costs to industry in both direct financial costs and those related to lost opportunities. Such a framework will explicitly assess risk and incorporate adaptive management of the industrial process and development (Boyd et al., 2008; Figure 6.2).

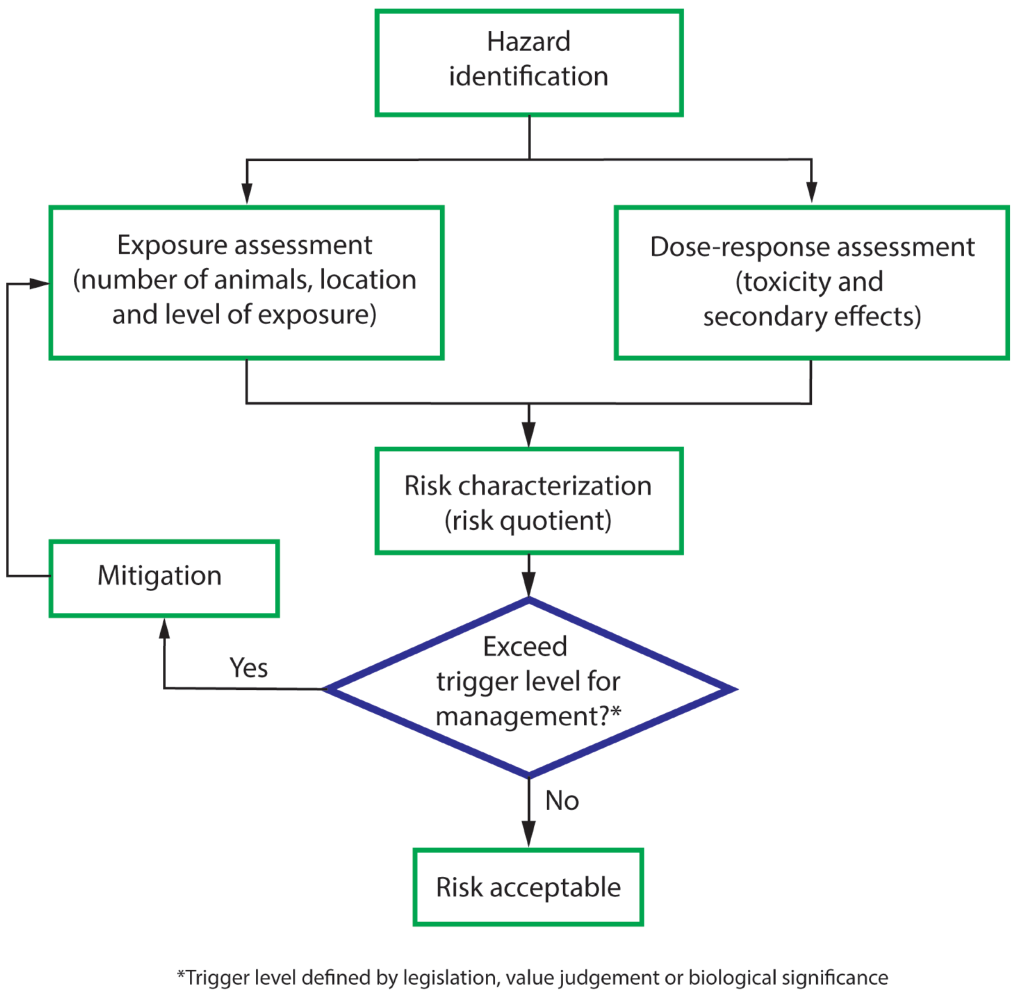


**Figure 6.2.** *An illustration of the information flow and decision pathway for a risk assessment process. This shows a feedback process involving mitigation when the risk exceeds the trigger level for management action. This is an adaptive approach to managing risk. Redrawn from Boyd et al. (2008).*

The advantage of a science-based framework for regulation of sound in the ocean is that it allows industrial activity to proceed in a precautionary manner and establishes procedures for collecting information about its effects as activity proceeds. Effects are then assessed against predetermined objectives. If those objectives are not met, mitigation is introduced, the mitigated activity is allowed to continue and is again assessed against specific objectives. This procedure is continued until a satisfactory operating procedure or design is found for the industrial activity. Many circumstances lend themselves to this approach, but some activities will always be found to be too harmful to continue.

The following sections expand on the activities needed to populate the risk framework illustrated in Figure 6.2.

***Hazard identification***

The main questions that will need to be addressed are

- Which sound sources need additional characterization?
- What can we do to develop acceptable (by industry, regulators, and stakeholders) standards and methods for measurement?
- Can we develop alternative sound sources to reduce impact where intense sounds are required (e.g., air guns replaced explosive sources for seismic surveys. Would it help to replace seismic air guns with marine vibrators?)
- What impacts do alternative sound sources have on the environment?
- What can be done to existing sound sources to reduce unwanted sound?
- How does industry measure its contribution to the ocean sound budget?
- What do we need to do to better understand the global background sound status?

***Dose–response assessment***

Quantifying the relationship between dose (i.e., received sound characteristics) and response (behavioral response, masking, TTS, PTS, injury) will be a task for Theme 2 (see Section 4.2).

***Exposure assessment***

Exposure assessment involves specifying the population that might be exposed to the hazard, identifying routes through which exposure can occur, and estimating the magnitude, duration, and timing of the dose that marine mammals might receive as a result of exposure. The information needed in this category includes the following:

- Distribution and abundance of specific organisms, such as fish and marine mammals, over long time periods to identify overlap between sources and receivers
- Quantification of industrial activity in the areas under question
- Assessment of how industrial activity translates into sound budgets
- Identification of stressors other than sound that act on the population of interest

Some of this information should already be available from management agencies, although the translation of industrial activities into sound budgets will be addressed in this theme (Section 6.3).

***Risk characterization***

Risk characterization involves the overall assessment of risk and is achieved by integration of information from the first three steps in the risk assessment process shown in Figure 6.2 (hazard identification, dose–response assessment, and exposure assessment) to develop a qualitative or quantitative estimate of the likelihood that any of the hazards associated with the sound source will occur. The information needs in this category include the following:

- Determination of whether any effects are biologically significant
- Definition of biological "hot spots" for animal production or especially sensitive species that should be avoided at times
- Measurement of the population growth in areas where sound is prevalent
- Definition of cumulative impacts in terms of how specific sounds can interact with other pressures

Again, management agencies should be able to provide some of this information, and Theme 2 will help define which effects of sound are biologically significant.

## 6.3 Routine sound monitoring

Although issues concerning the observation of sound are dealt with in detail by Theme 3 for the scientific purposes of the IQOE, Theme 4 also requires an element of sound measurement, particularly to characterize human-generated sound sources. Measurement of the characteristics of the sources of human-generated sound is required so that these can be used within sound propagation models (see Theme 1). Figure 3.3 shows the amplitude of different frequencies with distance from a pile driver. However, not only is it necessary to examine amplitude as in this case, but other characteristics of the sound also need to be determined, such as directionality, bandwidth, particle motion, pulse width, height, and rise time. The sound radiated from a source can vary with orientation and, for ships, their speed and whether they are loaded. In addition, a fuller understanding of how the characteristics of these sounds may change with propagation over larger ranges is required.

Even though sound from shipping is probably the greatest single source of human-generated sound in the ocean, this will not always be the case on local or regional scales. Pile driving is a fast-growing activity in some coastal regions, mainly because of the construction of offshore wind farms. Seismic surveys using air guns are also widespread. Other sources of marine sound include—but are not limited to—construction, dredging, acoustic communications, supersonic aircraft, ammunition, explosives, seismic exploration for scientific purposes, marine mining, cable laying, and naval training and surveillance sonars. The many types of sources and their associated sounds make it necessary to identify a way of quantifying them to make meaningful comparisons. One proposal for doing so is to determine their contribution to the total acoustic energy in the sea (Ainslie et al., 2009; Ainslie and Dekeling, 2011). Although sound spectral characteristics for many of these sources are available as examples that may (or may not) typify those types of sources, there is a need to compile information about these different sources and the extent to which they can be described by typical examples. The compilation then needs to be made available and the IQOE will promote this by developing a Web-based repository for spectral information about sound sources.

The IQOE will also adopt and promote standards for characterizing the sound from different sources, such as helping to develop and promote an International Standards Organisation (ISO) standard for radiated sound from ships in deep water. Such a standard is being developed by an ISO subcommittee devoted exclusively to underwater sound, and its effect on aquatic life. The IQOE will collaborate with the subcommittee in the adoption of appropriate standards for ships in shallow water as well as for sounds from other sources such as air guns, impact pile drivers and explosions, and for ambient noise (Cato, 1997; Carey and Evans, 2011). An essential prerequisite for all of these standards is the development of an acoustical terminology standard (Ainslie, 2011). The IQOE will promote these standards through the provision of Web tutorials about their application.

In many regions, statutory monitoring of sound levels is taking place around offshore developments or is being implemented by regional management authorities in response to wide-ranging legislation concerning management of the marine environment. This includes the Marine Strategy Framework Directive in European waters, where there is a commitment to establish guidelines to regulate human-generated sound in the ocean even though there is considerable debate about what these guidelines should be.

Methodological standards need to be developed for ambient sound measurements over long periods, to allow legislative standards to be established and enforced. The outcomes of both Themes 1 and 3 will support this requirement, and the presence of observatories established for the statutory monitoring of marine noise also presents opportunities for low-cost data collection in support of research with broader objectives.

Sound recording systems of this type are likely to become routine in the future, and the IQOE has the opportunity to influence the design of monitoring protocols, the hardware systems for carrying out monitoring, and the data storage and analysis systems, and also to benefit from these systems. However, to achieve these goals, the IQOE will need to engage closely with those who are responsible for establishing sound monitoring to maximize these benefits. Figure 6.3 illustrates a system of sound monitoring on a local scale that has been developed by both regulators and ship operators to solve a conflict caused by ship strikes on northern right whales. This system uses acoustic detection of the right whales to alert the ships to their presence.

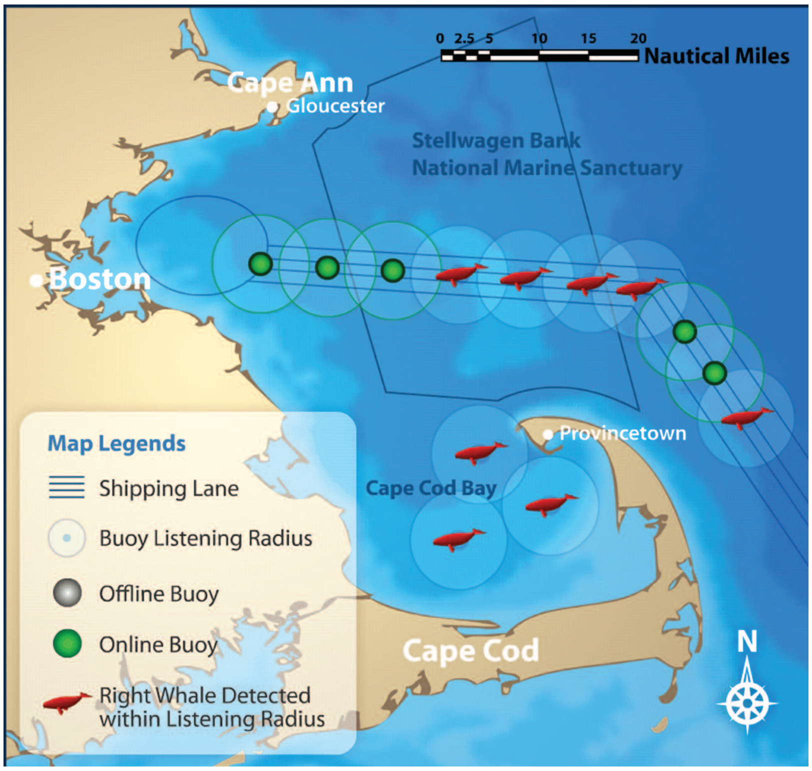


**Figure 6.3** *Diagram showing a real-time auto buoy system that is operational off the northeast coast of the United States. The system alerts mariners to the presence of right whales to reduce the probability of ship strikes. From Van Parijs et al. (2009). Used with permission from Inter-Research Science Center.*

## 6.4 Research priorities for regulators and industry

***Develop practical solutions, useful to industry and regulators, to monitor and mitigate human-produced sound***

The effects of specific doses of sound on protected species—as well as other species that may have ecological or economic value—is important for regulators and, therefore, also for industry. From an industry and regulatory point of view, while it would be ideal to understand the mechanisms underlying adverse effects such as permanent loss of hearing (permanent threshold shifts: PTS), there is a greater need to move quickly to develop precautionary indicators of significant effects, such as using temporary threshold shifts (TTS) as a safe indicator for risk of PTS. This will facilitate studies that define simple, but robust, empirical relationships between sound and responses in marine organisms. For example, the behavioral responses of beaked whales to sonars (Tyack et al., 2011) are an indicator of potential harm. Translating the probability of behavioral disturbance into a probability of a significant population effect can probably be achieved relatively easily, but with low levels of confidence. Additional work will then be necessary to increase the confidence around the estimated level of effect. However, for the time being, the thresholds of behavioral disturbance found in this case are the precautionary threshold that may be used by regulators.

Studies concerning individual impacts can deal with behavioral response, masking, TTS, and auditory or nonauditory injury. Although it has been shown that, in some cases, sound can injure or even kill individual organisms, population-level consequences would be unlikely if only a small proportion of the population is affected. In contrast, behavioral and masking effects can occur at lower sound levels and over vastly larger areas, and therefore may affect a larger and potentially significant portion of the population.

The effects of multiple sound exposures (both sequentially and simultaneously) may accumulate and add to the effects of other stressors, such as of ship collisions with northern right whales (Figure 6.3); the IQOE needs to consider such cumulative effects. Therefore, the program will undertake modeling to examine how the measured, usually adaptive, responses of animals to underwater sound can be rescaled to develop realistic representations of risk to populations. Much of this will be done within the PCAD modeling framework (Figure 2.5).

The research needed to define biological significance of sound for marine organisms can be summarized as follows:

- Better identify the effects of underwater sound on individual marine animals, to make it possible to scale up the problem through the accumulation of effects on individuals to populations. This could involve investigations of the following:
    - Temporary threshold shift (TTS): More studies are needed to assess temporary threshold shifts for risk assessments;
    - Behavioral effects: There is very little understanding on the behavioral effects of sound on marine life; and
    - Masking of sound signals used by animals for communication: Experimental evidence of consequences of masking is required, rather than relying on predictions based on modeling.
- Determine the spatial distribution of sensitive species and how this changes through time as a way of defining critical habitats for industry to avoid.
- Determine whether the PCAD approach can provide practical solutions to the problem of regulating sound production by industrial activity. Both industry and regulators may need solutions that are less precise, but more tractable.
- Provide key information to make feasible a risk-based approach to adaptive management of industrial activity when faced with high uncertainty about the effects of sound.

***Key questions***—Industry and regulators have identified the following important questions:

- What is the effectiveness of existing monitoring techniques and tools and how can they be improved?
- What additional monitoring tools (short- and long-term) can be developed to assist in marine mammal observations?
- Can International Maritime Organization (IMO) data be used as an analysis tool on a local and regional basis?
- Are "soft-start" or "ramp-up" effective mitigation techniques?
- Are there other ways to mitigate unwanted sound, for example, air bubble curtains?

For all industrial activities, a fuller understanding of existing and projected trends in industrial activity levels and sounds produced by these activities is important. While the IQOE will not aim to use active acoustics, a potential research topic for the project will be to help industry and regulators evaluate the impacts of active acoustic methods they use or intend to test.

In spite of its apparent prevalence, the importance of shipping sound for marine life is largely unknown. Shipping sound has the potential to mask the communication signals of marine mammals and fish, and both taxa have been shown to change behavior in reaction to these sounds. However, even though predictions based on theory indicate that communication ranges can be decreased as a result of increased sound levels, understanding the true extent of this effect is critically important. Many, if not most, species have developed mechanisms to compensate for masking, for example, increasing the source level of their sounds when located in an increased noise environment (Parks et al., 2010). There are also large differences in potential effects between deep and shallow waters and among the taxonomic groups affected.

Cavitation sound by propellers is an important source of shipping sound, so mitigation attempts could be targeted there. The Marine Environmental Protection Committee (MEPC) within IMO has formed a correspondence group on sound from commercial shipping that deals with mitigation measures such as ship-quieting technologies. Propellers are likely to be redesigned as a response to requirements to make more efficient propulsion. Sound radiation should be considered as part of the design process from the start.

Impact pile driving, used particularly for installation of offshore wind farm turbines, has been shown to lead to wide-ranging behavioral impacts on small odontocetes, such as harbor porpoises, and can injure marine life close to the source. This issue has been addressed in some regulations such as the EU *Marine Strategy Framework Directive* (also see OSPAR, 2009). Although marine pile-driving is generally well regulated in many regions and Environmental Impact Assessments (EIAs) are often required, cumulative effects of multiple piling activity, or cumulative effects of piling with other stressors (acoustic and nonacoustic) are not well understood and are beyond the scope of individual EIAs. Furthermore, particle acceleration is a primary concern for fish, especially in the near field, and should be measured directly in situ.

In examining the effects of seismic air guns on marine life, the International Oil and Gas Producers (OGP) has set a commendable example of the engagement of industry in researching acoustic impacts through the Joint Industry Program (OGP-JIP). While there are currently ongoing studies of the source characteristics of seismic air gun arrays, among a range of other studies (e.g., behavioral response study of Australian humpback whales to seismic air gun exposure), there remains a need for further research on the topics of behavioral effects, masking, and efficacy of mitigation measures.

Additional sound sources to be considered include naval sonars, cable laying, acoustic mapping, seismic exploration, deep-sea mining, wave- and tide-energy generation, new exploration technology, dredging, echo sounders, active positioning systems, and acoustic deterrent devices used in fish farming, among a range of others. Development of new technologies, such as marine vibroseis, that replace, where possible, existing sources, is strongly encouraged if there is evidence that the new source has lower impact.

***Research approaches*—**Research needed by industry and regulators to determine how best to conduct routine sound monitoring can be summarized as follows:

- Define what is meant by “routine sound monitoring.” For example, it is not always clear whether this should include measurements of specific activities, monitoring of ambient noise, or both.
- For ambient sound monitoring, it is necessary to identify the objective of meaningful and valued outcomes. Monitoring ambient sound can produce sound maps and sound budgets, and can identify trends of ambient sound over predetermined time scales in specific areas. This last objective is required, for example, by the EU Marine Strategy Framework Directive. Each of these objectives could require different approaches.
- Modeling sound propagation will be an important approach in designing monitoring networks and also for analyzing data.
- The development of compliance monitoring for sound levels at regional scales will require several steps, including
    - Identification of existing ambient sound measurement data within the study area.
    - Identification of suitable measurement systems (there is a database on suitable devices).
    - Identification of existing ocean observatories in the study area.
    - Assessment of the feasibility of using existing observatories for ambient sound monitoring.
    - Identification of representative sites

(including pressure areas or areas of high sensitivity) and the possibility of establishing reference areas where there is little human-generated ambient sound to describe natural fluctuations.
    - Development of a work plan, including a maintenance schedule and data analysis reporting cycle.
- If ambient sound monitoring is attempted in sensitive areas, the distribution and abundance of sensitive receivers (marine mammals and fish sensitive to the source in question) need to be documented to a higher standard than elsewhere so that there is sufficient statistical power to detect important changes in population status, and to be able to report these in sufficient time for management action to be taken.
- Sound frequencies that are most biologically important should be monitored. Consequently, it is necessary to define these frequencies.
- An investigation of the costs and benefits of monitoring is needed to ensure that the outcomes lead to a net benefit for society.

These tasks will need to be coordinated with the activities of Themes 1 and 3.

***Measuring the relationship between industrial activities and sound levels***

Compiling sound budgets (Nystuen et al., 2010) for a region is an approach used to establish or regulate the contribution made to the sound field by different industrial sources. It is likely that regulators could establish levels of anthropogenic sound within regions that cannot be exceeded and different industrial users of the ocean may have to work to remain within this limit. In this case, sound budgets, and perhaps allocation of sound credits to different ocean users may become commonplace. Compiling inventories of anthropogenic sound in a region may, therefore, be an important factor in establishing whether regulatory targets have been met. Industry will need to have simple and cost-effective tools for demonstrating compliance as well as real-time feedback to allow optimal decision-making during marine operations. For example, if the captain of a container ship knows the radiated, speed-dependent sound profile of the ship and also knows the contribution that the ship is allowed to make to the sound budget of the region, the captain can make a judgment about the speed at which the ship can travel, while also knowing that if the ship exceeds this speed, its excess contribution to the sound budget may be detected. Regulation is moving toward developing sound budgets, but we do not currently have the mechanisms in place for monitoring and feedback to optimize human behavior in a way that matches aspirations to control sound levels.

Some progress may be made through the compilation of sound inventories that quantitatively assess the contribution and characteristics of different sources to the overall sound field in a given region. Such compilations can be used to identify research and regulation priorities. Furthermore, sound inventories might help in determining whether, and to what degree, human activities contribute to the ambient sound field. Thus, they are tools that can be used in marine management.

Robust, validated models of ambient sound are also likely to be a tool for marine spatial planning and informed regulation. The need extends from regional areas of heavy traffic to ocean-basin scales.

***Key question***—The key question for this topic is:

- How can the observed sound field in specific locations be accounted for, based on known sources and propagation conditions?

To answer this question will require the development of models that will depend on

- establishing long-term sound measurements (see Theme 3),
- cataloging sound sources (see Section 6.2.2),
- integrating these into propagation models (see Section 3.3), and
- validating these models with direct observations (see Section 5.1).

Validated models can be used to evaluate the effectiveness of sound-constraining regulation to allow planners to examine the implications of different options for offshore development.

## 6.5 Implementation approaches

The IQOE will work with the IMO to further address the issue of shipping sound as one of the main contributors to undersea sound. The IQOE will work in collaboration with industry groups to develop a joint working group on the issue of underwater sound to strengthen the links between industry and research. This should be supported by a clear communication and outreach plan to convey the results of the IQOE to global stakeholders, policymakers, and the public (see Chapter 7).

The IQOE will, as far as possible, promote the use of scientific results to harmonize national regulations. There is a danger of different standards being applied by different countries, resulting in confusion and adding unnecessary costs for industry. Although the regulation of human activities is a policy decision that is based on more than scientific facts, the same results could be used very differently across national boundaries. For example, many EU member states set priorities for underwater sound in very different ways. Researchers operating within the context of the IQOE have an opportunity to help harmonize the foundation of scientific information behind the decisions of environmental management. Wherever possible, environmental management should be based on empirical studies and standardization of measurement techniques globally. Standardized soundscape measurements developed through the IQOE can provide the long-term data that could be used to assess and monitor soundscape parameters in ecologically significant areas, such as marine protected areas.

# Chapter 7
# Implementation

## 7.1 Introduction

The preceding chapters present a case for a decade-long program of observations, modeling, and research related to sound in the ocean and its effects on marine organisms. Key questions are presented, as well as some general approaches for addressing these questions. The project priorities were developed based on an open science meeting. As with many international research projects, implementing this project will require additional discussions, meetings, and documents. However, the following will outline enough details of implementation to provide the sponsors (organizational and financial) and project scientists with a foundation on which to build the project.

## 7.2 Fundamental questions

Underlying the IQOE are five fundamental questions:

1. How have human activities affected the global ocean soundscape compared with natural changes over geologic time?
2. What are the current levels and distribution of anthropogenic sound in the ocean?
3. What are the trends in anthropogenic sound levels across the global ocean?
4. What are the current effects of anthropogenic sound on important marine animal populations?
5. What are the potential future effects of sound on marine life?

Questions 1-3 will be addressed by Themes 1 and 3, which focus on soundscape modeling and acoustic observations, respectively.

Questions 4 and 5 will be addressed primarily by Theme 2 (effects on sound on marine organisms), although the work carried out within Themes 1 and 3 will also be relevant. Theme 4 addresses how the results of the new research and observations will apply to management and regulations. Theme 4 will need to integrate information from Themes 1-3.

Each theme is divided into key questions and research approaches to each of these questions. Each theme will attract a different kind of scientist, but there will need to be an unprecedented level of cooperation among ocean acousticians, marine biologists, engineers, observing system specialists, data experts, and communication specialists to ensure the success of the IQOE.

## 7.3 Timeline

An approximate 10-year timeline is planned for the IQOE. This is the usual duration for large-scale ocean research projects, providing enough time to conduct detailed planning and foundational activities, raise funding for research, conduct new research and observations, and synthesize the results obtained. The community of scientists involved at the IQOE Open Science Meeting was enthusiastic about a decadal project. It is recognized that a project lasting only one decade will not be able to characterize how the effects of sound change with climate cycles—such as the El Niño – Southern Oscillation and North Atlantic Oscillation—that are repeated only one to a few times per decade. However, most funding agencies are reluctant to commit to projects longer than 10 years' duration.

The project will be implemented in four phases:

1. Laying the foundation (Years 1-3)
2. Pilot projects (Years 4-6)
3. International Year of the Quiet Ocean (Year 7)
4. Synthesis (Years 8-10)

The phases will not be strictly sequential. For example, planning for later phases will begin before Phase 1 is completed. In addition, some national programs have already begun implementing new observing systems in anticipation of the IQOE.

***Phase 1. Laying the foundation***

As with other international research projects, it will be important in the first few years to establish standards and data management mechanisms, and to synthesize as much available information as possible to provide a foundation for new observations and research, and to identify gaps in information that can help guide new activities.

**Standards and intercalibrations—**It will be important to come to agreement among project scientists regarding standards for acoustical and biological measurements before any large-scale observations and experiments are conducted. Standards are important so that data collected by different scientists in different locations can be compared and compiled into global databases. Establishing standards may require meetings of individuals who possess expertise in making observations and experimental measurements. Intercalibrations may need to be conducted related to equipment and methods for observations. Intercalibration exercises are especially important when different research groups or observation systems use different equipment and techniques. Intercalibration may require workshops in which the most common systems and methods are tested against each other in the same location with the same acoustic and biological signals. Standardization and intercalibration may also be improved through training workshops.

**Data management—**The IQOE will establish a data management and communication (DMAC) activity, which will be responsible for establishing procedures and guidelines for data collection and assembly, and communication of data to users. Well-designed data management is crucial so that properly standardized and intercalibrated data are stored in a common location to create global datasets that can be analyzed by project scientists and eventually be openly available for reuse by other scientists and managers.

**Synthesis of available data—**A great volume of acoustical data and data from experiments on biological effects have been published in the peer-reviewed literature, as well as in government and industry documents. Compiling and synthesizing such data will provide a foundation for IQOE research and observations, avoid unnecessary duplication of scientific activities, and lead to identification of gaps in existing data and information.

It is envisioned that the first three years of the project will focus on the above three areas and they will be approached through a series of small workshops:

- Synthesis of activities on soundscape modeling: The IQOE cosponsored a workshop on Predicting Sound Fields, held on 15-16 April 2014 in Leiden, Netherlands (with the International Whaling Commission, the U.S. National Oceanic and Atmospheric Administration, the U.S. Office of Naval Research Global, the Netherlands Organisation for Applied Scientific Research, and the Netherlands Ministry of Infrastructure and the Environment). The report of the workshop can be found at http://scor-int.org/IQOE/Leiden_Report.pdf.
- Workshop on design of IQOE data collection, management, and access. Issues related to standardization of data collection and storage will need to be addressed early in the project. The goal of this workshop will be to agree to standards and procedures that would guide the IQOE to make observations and research conducted in different locations comparable. The workshop will involve representatives from as many existing observing systems as possible, and will include members of existing standards groups such as the ISO ISO/TC 43/SC 3 on Underwater Acoustics.
- Workshop to synthesize data on the hearing capabilities of marine organisms.
- Workshop to set standards for ocean acoustic observations and experiments with marine organisms. The ISO ISO/TC 43/SC 3 on Underwater Acoustics will be consulted to plan this work.
- Meeting with industry representatives regarding their participation in the IQOE. The goal of this meeting will be to produce one or more memoranda of agreement between the IQOE and industry groups. This meeting also could result in the creation of an industry advisory group to the IQOE. The meeting may result in a standing working group of the IQOE that will focus on industry engagement. Such a working group will be necessary to ensure that Theme 4 is linked properly with the other themes and that the project is generating the information to answer the questions in Theme 4.
- Workshop on access to proprietary and classified information, past, and future. Success of the IQOE will depend on access to past data collected by navies, commercial oil and gas exploration companies, and the Comprehensive Test Ban Treaty Organization. Data collected as part of the IQOE will need to take into account sensitivities of stakeholders about collection and public access to acoustic data. The goal of this workshop will be to identify potential providers of information, what data they will make available, under what circumstances. The workshop will also discuss a process for developing written agreements about data sharing.

Other potential workshop include the following:

- Workshop to develop a world map of anthropogenic ocean sound (see Example 1 below). This workshop will work as far back in time as possible to determine whether it is possible to develop time series for ocean sound similar to the time series for atmospheric $CO_2$ concentrations known as the Keeling Curve (Keeling, 1960). This workshop will produce a paper for a high-profile journal.

- Workshop to plan an Arctic Ocean acoustic survey (see Example 2 below). This workshop will need to bring together scientists involved in acoustics of the Arctic Ocean, as well as organizations involved in Arctic Ocean science and observations. This workshop will produce a plan for an Arctic Ocean experiment that will be part of the IQOE.
- Workshop on the use of sound as an indicator of environmental status. This workshop will maintain close ties with the EU's Marine Strategy Framework Directive and will provide a world forum in which to discuss the meaning of "Good Environmental Status," how it is affected by underwater sound, and how changes in environmental status might be monitored using sound as a tool (see Example 3 below). The workshop will critically evaluate acoustic measures proposed for Good Environmental Status on an international basis and relating cost and reliability to effectiveness of different measures.
- Workshop on global ocean acoustic observations. The workshop will seek commitments from observation systems to install and support suitable hydrophones, as well as to identify areas of the global ocean where new hydrophone systems should be deployed. The workshop will produce a white paper that might be published in the peer-reviewed literature.
- Workshop on opportunistic observations. It will be necessary early in the project to establish mechanisms to identify opportunities related to changes in shipping lanes, planned large-scale pile driving activities, and other opportunities to study before, during, and after noise levels and effects on marine organisms. This workshop will conduct detailed planning for opportunities that have already been identified, as well as look forward to identify future approaches. The goal of this workshop will be to produce detailed plans for IQOE observations and experiments related to known opportunities, as well as a document that will specify how future opportunities will be approached.

***Phase 2: Pilot projects***
The information available from Phase 1 of the project will make it possible to proceed to Phase II, consisting of pilot projects. The purpose of the pilot projects will be to test the approaches described in this Science Plan in specific well-studied locations, with the intention of scaling up the approaches to more locations or a wider geographic range in Phase 3. This phase will also include planning for Phase 3.

***Phase 3: International Year of the Quiet Ocean (IYQO)***
An objective of the IYQO will be to conduct intensive and coordinated research, observations, and modeling worldwide and at large scales simultaneously. Phase 3 will be an intensive 12-18 months of acoustic observations and experiments worldwide, based on the information developed in Phase 1 and the experience gained from Phase 2. The IYQO will be used as a focus of public attention on sound in the ocean. Planning the IYQO for a single year has precedents in the International Geophysical Years (IGYs) and International Polar Years (IPYs). These events have resulted in both intensive research and observations in the focal year (or 18 months for IPYs) and sustained research and observational focus beyond the focal period of time.

***Phase 4: Synthesis***
Synthesizing data from the IYQO and reporting on studies carried out during Phase 3 will require several years to complete, partly because of the potential complexity of the data that will emerge and also because of the time that required to analyze them. It is likely that an open science meeting will be held toward the end of this period to report on the accomplishments of the IQOE and to discuss legacy activities.

## 7.4 Operating approach

The IQOE will be structured as a coordinating mechanism for all researchers with an interest in underwater sound and its effects on marine organisms and who are willing to pursue IQOE objectives within the boundaries of IQOE standardization and data sharing requirements.

Research will be funded through traditional national, regional, and international funding sources, such as agencies that fund research and observations (such as the National Science Foundation in the United States, the European Commission and national funding agencies worldwide, possibly through groupings of agencies such as the Belmont Forum). Any research that will be part of the IQOE will need to be approved by an IQOE Steering Committee (see Section 7.6). The Steering Committee will apply standards associated with the planning, data collection and reporting and will monitor progress of the collected set of IQOE-endorsed scientific activities. In return for complying with IQOE standards, researchers organizing specific studies will benefit from being a part of the process that defines the data standards, organizes outputs into common formats, and provides central coordination of data management and modeling. In addition, they will be a part of a community that achieves the critical mass sufficient to sustain a high profile within the stakeholder community and that provides representation for their scientific outputs to policymakers, industry, and the public.

## 7.5 Governance

The IQOE will derive its authority from its organizational cosponsors, the Scientific Committee on Oceanic Research (SCOR) and the Partnership for Observation of the Global Oceans (POGO). These organizations also provide the international context within which the IQOE will operate. However, it is possible that national or regional subsections of the IQOE may develop, especially through collaboration in regional experiments.

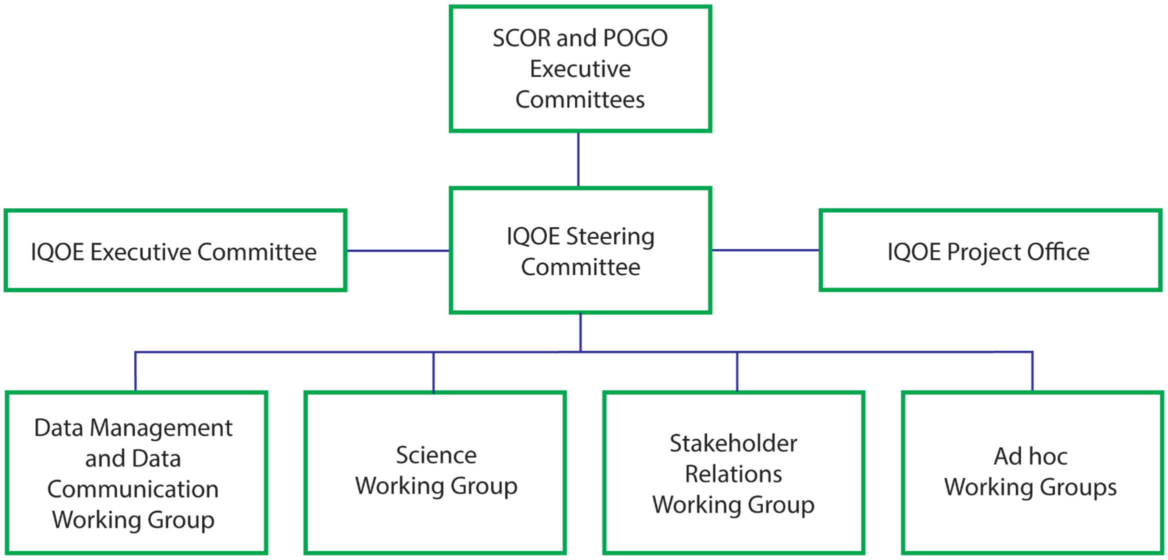


**Figure 7.1.** *The governance structure of the IQOE. The IQOE is established within the authority of SCOR and POGO. Lines on this diagram show routes of communication within the overall structure.*

Operational governance of the IQOE will be the responsibility of the Steering Committee (Figure 7.1). This committee and its chair(s) will be appointed by SCOR and POGO. The chair(s) of this Steering Committee will report annually to SCOR and POGO about all aspects of the IQOE, including progress in implementing the Science Plan, outreach, and stakeholder engagement. The SC may have joint chairs, particularly representing biological and acoustical expertise. The SC will be formed of its chair, the chairs of the permanent working groups, and as many as 10 additional members. The current plan is to have three standing working groups:

(1) *Working Group on Data Management and Communication* will have responsibility for defining the standards of data collection and managing the various systems used by the IQOE for data communication, including the Web site and associated data portal.
(2) *Science Working Group* will have responsibility for determining whether projects proposed by the research community should be included within the IQOE.
(3) *Stakeholder Relations Working Group* will establish communication with the shipping industry, oil and gas developers, navies, the CTBTO, and other groups with interests in IQOE science and could provide access to new sources of data.

Much of the international coordination and planning of the IQOE will be conducted by ad hoc working groups, each of which will be established to perform a specific task related to the IQOE objectives. Such tasks could be to conduct a specific experiment or study, but could equally be associated with coordination of public outreach or stakeholder engagement.

Appointments to working groups will be the responsibility of the Steering Committee. The IQOE will be managed on a day-to-day basis by the IQOE Executive Committee, which will be a subset of the IQOE Steering Committee.

## 7.6 Project management

Following review and approval of the Science Plan by the sponsors, the Steering Committee will be selected by project sponsors. The Steering Committee will have the following responsibilities:

- Manage implementation of the IQOE Science Plan and coordinate IQOE activities among different nations.
- Oversee the budget of the project.
- Establish appropriate policies for data management and sharing, and for standards and intercalibration to ensure that IQOE data collected by different investigators are comparable and to promote sharing and preservation of IQOE-related data.
- Collaborate, as appropriate, with other related programs.
- Create and implement the communication strategy (see Section 7.7).
- Report annually to SCOR, POGO, and any subsequent sponsors, on the state of planning and accomplishments of the IQOE.

SCOR will provide the primary administrative support for the IQOE, at least initially. The project may eventually require two or more staff persons (one person specializing in data issues and the other in logistics) to help implement and represent the IQOE. Duties that will need to be handled by an IQOE International Project Office include

- helping the Steering Committee with logistics for meetings and publications,
- representing the project at various meetings,
- fund-raising for project activities, working with the Steering Committee and sponsors,
- communications and outreach, including Web site and newsletter, and
- management of data.

Many international projects benefit from the creation of national committees, which can lead national efforts for planning science activities, fund-raising for these activities from national sources, promoting national data management activities, promoting capacity building, etc. The IQOE will investigate the formation of national and regional project committees. These could be particularly relevant in relation to basin-scale observations and experiments. The chairs of these national and regional committees will be ex officio members of the IQOE Steering Committee.

## 7.7 Communication and outreach

The IQOE Steering Committee will develop a communication strategy at an early stage. This strategy will identify all the major stakeholder groups and define the methods that will be used to communicate the purpose and results of the IQOE, as well as to encourage the involvement of stakeholders, when appropriate. This strategy will lead to the provision of publications and other materials that will allow those associated with the IQOE to provide a consistent and clear message.

The broader objectives of the IQOE include improved public appreciation of the ocean, the life within it and pressures upon it. Opportunities exist to stimulate the development of "citizen science" projects by streaming spectrograms in real time from observatories and by providing possibilities for the public to record sounds of marine organisms (e.g., through an iPhone application) and to upload these recordings to a Web site with an accompanying photograph. Links with Google and social networking will be important to encourage broad uptake of IQOE activities and information.

A comprehensive plan for the engagement of stakeholders and the public will be a priority for the IQOE. This plan will include targeted activities that reach policymakers, industry representatives, the media, and other stakeholders. Strategic activities will build awareness of the IQOE's research portfolio and encourage the participation of important industries in research activities.

***Program "launch"***

To accomplish IQOE goals within an international framework, it is essential that the program becomes widely known as a credible and trustworthy source of authoritative information and a basis for new measurements and new understanding of the effects of sound on marine life. An initial outreach and communications effort should reach professionals and scientists working on related research, print, and broadcast news media; the scientific community at large; stakeholders (e.g., policy and decision-makers, fishers, oil and gas industry representatives, and the environmental community); and the public to increase awareness of the IQOE, its mission, and potential projects. Public trust and confidence in the IQOE is critical and will be advanced as these parties become convinced of the scientific integrity of the research being conducted by the program's participants and discover the utility and timeliness of the products created by this significant international research effort.

The long-term viability of the IQOE will depend on broadly based funding from government, industry, and private sources. This funding will only come if the program achieves broadly based public support. A highly focused and vigorous outreach program to develop the credibility of IQOE activities and eventually inform stakeholders and the public of the program's achievements will play a fundamental role in building this support and ensuring the program's long-term viability. To help achieve this credibility, the IQOE will work to develop a consistent image and a consistent message.

It is recommended that the program be "launched" with a suite of activities that include a scientific symposium and public lectures to engage the public, scientific community, and other stakeholders.

***Central Web portal***

A Web portal will provide a convenient "entry point" for the internal project participants and external community. It should reflect and highlight the state-of-the-art research by IQOE scientists. It should provide overviews and links to and from each field project. The portal should include a password-protected section for IQOE project participants, as well as openly available resources that will be useful for public purposes. Integrated social media should be considered in developing the site. Provisions will also be necessary for cataloging image, audio, and video files.

***Interactive online database***

An online database must be developed to allow for the cataloging, sharing, and archiving of program data. It should provide open data access for public uses. Periodic online training on how to use the data tools and contribute to the database will be important.

***Media relations***

The ongoing work of the IQOE will be brought to the attention of the international news media, and relationships between media and project representatives must be established. Resources such as "backgrounders" on important issues and new findings should be available on the central Web portal for the media, as well as audio and video material.

***Highlights reports***

Stakeholder and public interest can be developed through the sharing of new discoveries and research findings in well-publicized annual "highlights" reports. The release of these reports should be timed to coincide with an annual international media campaign.

***Partner resources***

It is essential that the IQOE gains the attention and support of public officials and other stakeholders worldwide. To help facilitate this attention and support, a suite of informational materials should be developed, which can be easily replicated, translated, and distributed by program participants. Common resources will assist project partners in communicating about the program and engaging stakeholders in their regions. These resources could include fact sheets, maps highlighting ongoing research, and reproducible graphics. It is also important that the program have a consistent "graphic identity" that is print and Web friendly. Other resources could include PowerPoint presentations, archived webinars, print materials, applications, and graphic visualizations.

Engagement of stakeholders is critical in all these processes. In fact, many data are already available, for example, as recorded in various environmental assessments, and these data should be made more widely accessible. Initiatives engaging the industry such as the International Oil and Gas Producers (OGP) Joint Industry Program and the recently formed working group on underwater sound within the Central Dredging Association (CEDA) are important first steps. In general, important roles will be played by the industry associations such as OGP and crucial international bodies such as the IMO and NATO to help us fill the knowledge gaps.

As an example of what should be possible on a larger scale, the Discovery of Sound in the Sea (DOSITS http://www.dosits.org/) program has developed a public Web site and an educational program for students and teachers from primary school through college. The Web site introduces the full range of science and issues associated with sound in the ocean. Ecological Acoustic Recorders (EARs) were developed by the Census of Coral Reefs project of the Census of Marine Life for monitoring of coral reefs, including the appraisal of coral reef biodiversity, activity of sound-producing organisms, and human activities in reef areas (Lammers et al., 2008). Sounds recorded by EARs can be heard at http://www.pifsc.noaa.gov/cred/ear_sounds.php. A variety of Web sites such as that described by André et al. (2011) aggregate real-time and archived acoustic data from a range of sites worldwide, making them available online. There are many other examples of sound from marine organisms available through the Aquatic Acoustic Archive (http://aquaticacousticarchive.com/) and DOSITS. Coordination with these kinds of established and successful outreach programs will be important for rapid ramp up of IQOE activities in these areas.

Promotion of the use of acoustics within the wider marine science community should be a further spin-off from the

IQOE. Researchers often do not use acoustics where it could actually benefit their research (and conversely their research can benefit the overarching questions being addressed by this project). These missed opportunities are largely because specialized acoustic technologies used to be complex and costly, which limited their accessibility. However, the means now exist to make cost-effective acoustic recording and data logging devices that can be readily used by other researchers without recourse to specialized technical knowledge.

## 7.8 Education and capacity building

An important aspect of large-scale international research projects is to help build capacity for science related to the project. In part, this is accomplished through involvement of graduate students in the work of their advisors. However, the sponsors also expect their projects to encourage the development of science capacity in developing countries. Research on sound in the ocean and its effects on marine organisms can be carried out anywhere that hydrophones could be deployed, but it will be important to provide opportunities for scientists from developing countries to participate in the IQOE and to receive training as a result of the project. SCOR and POGO conduct a great deal of capacity building through their various programs. Some specific opportunities that could relate to IQOE topics include the following:

- POGO Visiting Professorships—POGO offers the opportunity for institutions in developing countries to host scientists from other countries (developed or developing) for periods of about six months, to serve as teachers and mentors, and potentially to conduct joint research (see http://ocean-partners.org/index.php/training-and-education/pogo-visiting-professorship).
- POGO/SCOR Visiting Fellowships for Ocean Observations—POGO and SCOR cofund a program that provides an opportunity for students, technicians, postdoctoral fellows, and other early-career scientists to visit an institution in another country to learn how to deploy and operate, and analyze data from, observing systems (see http://www.ocean-partners.org/training-and-education/pogo-scor-fellowship).
- SCOR Visiting Scholars—SCOR operates a program similar to the POGO Visiting Professorship program, the major difference being that the terms of SCOR Visiting Scholars are shorter (2-8 weeks) and SCOR does not require the host and scholar to be prematched (see http://www.scor-int.org/SCOR_Visiting_Scholars.pdf).

## 7.9 Relationship with other organizations, programs, and activities

The IQOE is being established in the context of organizations, other projects, and observing system activities concerned with sound in the ocean and its effects on marine organisms. The IQOE will make connections with these entities by inviting individuals involved in them to serve on the SC or other IQOE groups, through workshops of the project, and through regular communication. Some particularly important relationships will include the following:

- Observing systems—This report catalogs ocean observing systems that the community believes could be important for implementation of the IQOE (see Appendix II). These include the Global Ocean Observing System (GOOS)—which is a global consortium of national, regional, and international observing systems—as well as specific systems that may or may not consider themselves part of GOOS, but which either currently include hydrophones or to which hydrophones could be added. The IQOE will also contribute, where relevant, to the "Oceans and Society: Blue Planet" program, which is the marine task within the Group on Earth Observations (GEO), an intergovernmental body dedicated to the use of Earth observations for the benefit of society.
- Industry and regulators—The major sources of human-generated sound arise from industries such as shipping, oil and gas exploration and production, energy production, and disposal of unexploded munitions. It will be important through the life of the project to keep contact with the relevant ocean industries to ensure that their needs for information are being met and to gain access to sound data from industry that could be useful for IQOE implementation. The project will work with industry groups, as appropriate. Both POGO and "Oceans and Society: Blue Planet" are creating working groups for industry engagement, and the IQOE will link to these groups as they develop. Regulators of industrial activity and environmental quality are also major potential users of IQOE results, and the project will ensure communication with such organizations.
- Scientific community—Members of the Steering Committee will provide the primary linkage to the relevant portions of the scientific community, including acousticians, marine biologists,

physical oceanographers, and others. The IQOE will present information about the IQOE and its progress at international ocean science and acoustic meetings.

- Related projects—The IQOE is being developed in the context of other research projects that are seeking to understand the global ocean and how it is changing. This is the first international project with a general focus on effects of sound in the ocean on marine life, and there are no closely related research programs on this international scale. The IQOE will coordinate with national research programs on marine mammals and sound. On the international scale, other SCOR-sponsored projects are focused on ocean biology, and projects sponsored by other organizations are interested in aspects of physical oceanography and climate. These projects will be kept informed about the IQOE.

## 7.10 Work streams and workshops

The IQOE will build its activities around work streams defined by the scientific requirements of this Science Plan. Establishing where synergies and dependencies lie within the program structure will be an early task for the Steering Committee, but many of these relationships will only emerge as the IQOE develops. There are, for example, strong dependencies between progress in defining soundscapes and progress in observing and modeling ocean sound.

## 7.11 Funding

Funding for the IQOE Open Science Meeting was provided by the Alfred P. Sloan Foundation. Two kinds of financial support will be necessary to implement the IQOE. First, support for planning and coordination will provide a basis for science activities. Support for planning and coordination will be sought from national science agencies and other national sources, industry, other foundations, and nongovernmental organizations. This funding will be used to support activities of the Steering Committee and the International Project Office, and for the activities during Phase 1 of the project. The second kind of financial support will be national and multinational funding to conduct the research, observations, and modeling described in this Science Plan. This kind of support will be sought and obtained from traditional sources and will leverage the much smaller planning and coordination support. It may be possible to obtain industry support to a greater extent than is typical for international research projects.

For the Census of Marine Life, the funding provided by nations through traditional channels for science activities was approximately 10 times the amount of funding for planning and coordination provided by the Sloan Foundation. To implement the IQOE successfully, it will be necessary for individuals to use this Science Plan and subsequent documents as a basis for proposals to their usual national and multinational (in some regions such as the EU) funding agencies. The SCOR Secretariat will provide logistic support (with help from the POGO Secretariat) to the project until it can arrange funding for staffing.

## Example 1
# World map of anthropogenic ocean sound

**Objectives:**

- Produce a map of the Earth's oceans showing total acoustic energy (over a meaningful duration, e.g. one year) from human sources.
- Create layers for the different sources: shipping, seismics, pile driving.
- The map will highlight regions characterized by high levels of sound (hot spots) and other regions that are still relatively unaffected by human-generated sound.
- The map will be made publicly available (in print and in GIS data).

**Background and context:**

Several studies indicate that ambient sound in the ocean has increased significantly over the past 50 years (Andrew et al., 2011; Chapman and Price, 2011; Frisk, 2012) at frequencies below 500 Hz. Sound at such low frequencies travels across ocean basins with little loss of energy. These studies attributed the increases to distant shipping. The U.S. National Oceanic and Atmospheric Administration sponsored a workshop and project to develop a regional map similar to that proposed here, but for the U.S. EEZ (NOAA, 2012). A world noise map will begin to expand our understanding of the spatial and temporal variation in sound within important ecological regions that are changing rapidly, such as the Arctic Ocean.

**Approach:**

1. Identify key people who will be able to produce this map.
2. Identify the types of anthropogenic sources that can and should be included in this map.
3. Identify data needs and sources.
4. Devise modeling approach.
5. Arrange peer review of both the approach and the input data (e.g., through a workshop).
6. Write software and run the model.
7. Arrange peer review of the results.
8. Write and publish report and map in a high-impact journal (*Nature* or *Science*).

A model will be used to impose a grid on the Earth's oceans. The total number of hours that each source operated within each cell needs to be extracted from the underlying databases. Source levels need to be assigned to each source. Transmission loss models will be applied (varying by acoustic zone) to populate cells with received energy. Maps of cumulative energy will be produced for each source type (shipping, seismics, pile driving) and as a cumulative total. Validation of the map with field measurements will use long-term recordings and error analysis that will consider the effects on the modeled received level as a function of source depth and receiver depth, uncertainty in source level, variability in sound speed profile, uncertainty in seafloor geoacoustics, and other relevant factors.

The layers of the map will look similar to the shipping density map by Halpern et al. (2008), illustrated in Figure 7.2. The map will be in units of energy. The transform from a shipping density map to a cumulative energy map, however, will not be linear.

**Figure 7.2**. *Shipping density map. From Halpern et al. (2008). Reprinted with permission from AAAS.*

# Example 2
## Acoustic ecology of the Arctic Ocean: A survey along the ice edge

**Objectives:**

- Make recordings of ambient sound conditions in the Arctic Ocean, differentiating, when possible, anthropogenic, physical, and biological sound sources.
- Identify sounds from specific target study organisms, which may play an important role in ocean food webs. The goal here is to survey across the entire ecosystem (zooplankton-nekton), but also to target highly valued species like whales.
- Examine how the changing level of activities will change sound levels and where there is likely to be an intersection between the biology and sounds.

**Background and context:**

The Arctic Ocean is likely to be one of the most changed biomes as a result of climate warming. Loss of sea ice during summer and reduced ice cover in winter present opportunities for economic development that have hitherto been technologically impossible or not economically viable. In particular, the expansion of shipping traffic and the extension of oil and gas explorations and production into the Arctic Ocean are likely to be the main anthropogenic stressors. This is exemplified by the Shtokman gas field that exploits gas condensates and is estimated to be one of the world's largest natural gas deposits. These activities cause significant sound pollution (OSPAR, 2009). Considerable uncertainty exists around how these activities should be regulated in order to reduce their environmental effects.

**Approach:**

1. Assemble a team of acoustic and biological experts as a project steering group.
2. Determine the appropriate observation platform.
3. Conduct observations starting after the period of maximum ice extent in March, but before the minimum in September (see Figure 7.3) using a vessel transit of the NE passage back and forth close to the retreating ice edge.
4. Use dipping hydrophone arrays, towed hydrophones, bottom-mounted drifting buoys, and high-frequency scientific echosounders and profiling imaging systems.
5. Data from buoys and dipping stations will be used to quantify ambient sound levels.
6. Conduct targeted acoustic recordings of specific target species.

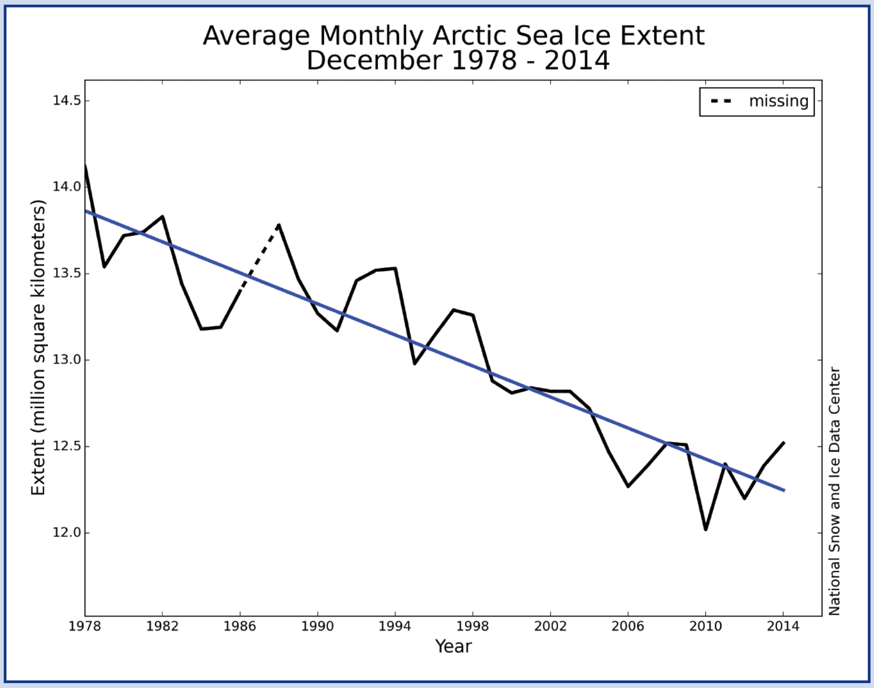


**Figure 7.3.** *Changes in Arctic sea ice extent over time. From U.S. National Snow and Ice Data Center, http://nsidc.org/arcticseaicenews/*

## Example 3

# Average ocean noise as environmental status indicator

**Objectives:**

- Monitor globally averaged low-frequency sound (“ocean noise”).
- Identify observations to monitor key components of ocean noise budget.
- Detect changes in the key components from measured ocean noise.

**Background and context:**

Several studies (e.g., Andrew et al., 2011) indicate that the level of ambient sound in the ocean has increased significantly since the 1960s at frequencies below 500 Hz. The level of ocean noise is sensitive to the number and strength of the sources (mainly ships; also whales and air guns) and to propagation conditions. Monitoring the globally averaged low-frequency sound (“ocean noise”) provides a useful indicator in its own right because of its possible impact on communication ranges of baleen whales (Parks et al., 2007; Stafford et al., 2007; Clark et al., 2009). It also offers the prospect of monitoring climate change through the propagation conditions (e.g., average temperature or wind speed) and changes in sources of sound (e.g., total sound power radiated by all ocean-going ships).

**Approach:**

1. Identify team able to monitor and interpret ocean noise collaboratively.
2. Develop instrumentation requirements.
3. Identify suitable site(s) for study.
4. Identify and gather key input data for feasibility study.
5. Model sound sources and propagation at site(s).
6. Measure sound field at site(s) and relate to key model input parameters.
7. Peer review (e.g., through a workshop) before proceeding to ocean scale.
8. Identify suitable ocean (suitable basin; suitable monitoring network).
9. Identify and gather key input data for selected ocean basin.
10. Model sound sources and propagation in ocean basin (see also Example 1, “World map of anthropogenic ocean sound”).
11. Identify and bridge critical gaps in hydrophone network.
12. Measure sound field in ocean basin and relate to key input parameters.
13. Assess feasibility for detecting changes in key parameters.
14. Write and publish results in a peer-reviewed journal.

Feasibility study: The purpose of the feasibility study is to mitigate the risk of an ocean-scale experiment by identifying and testing the methods in advance. An important aspect of the feasibility study is understanding how the geometry and frequency would scale up to a larger (ocean-scale) experiment.

Ocean basin study: After a progress review, monitor sound on an ocean scale. The choice of a suitable ocean depends on having a hydrophone network with wide coverage, for which best use will be made of existing CTBTO stations, Station ALOHA http://aco-ssds.soest.hawaii.edu/ALOHA/, and The PerenniAL Acoustic Observatory in the Antarctic Ocean (PALAOA) http://www.awi.de/en/news/background/palaoa_what_does_the_southern_ocean_sound_like/, as well as newly installed stations (EU Member States are required to monitor trends in low-frequency underwater noise from 2014). Additional hydrophone stations might be needed. To provide an indication of any trend, ocean noise will be monitored for a period of several years. The first result is the ocean noise itself, a possible proxy for global economic activity (Frisk, 2012). Because propagation conditions also depend on parameters related to climate change (e.g., sea surface temperature, pH), the possibility also exists of monitoring climate change through changes in the ocean noise (see Figure 7.4).

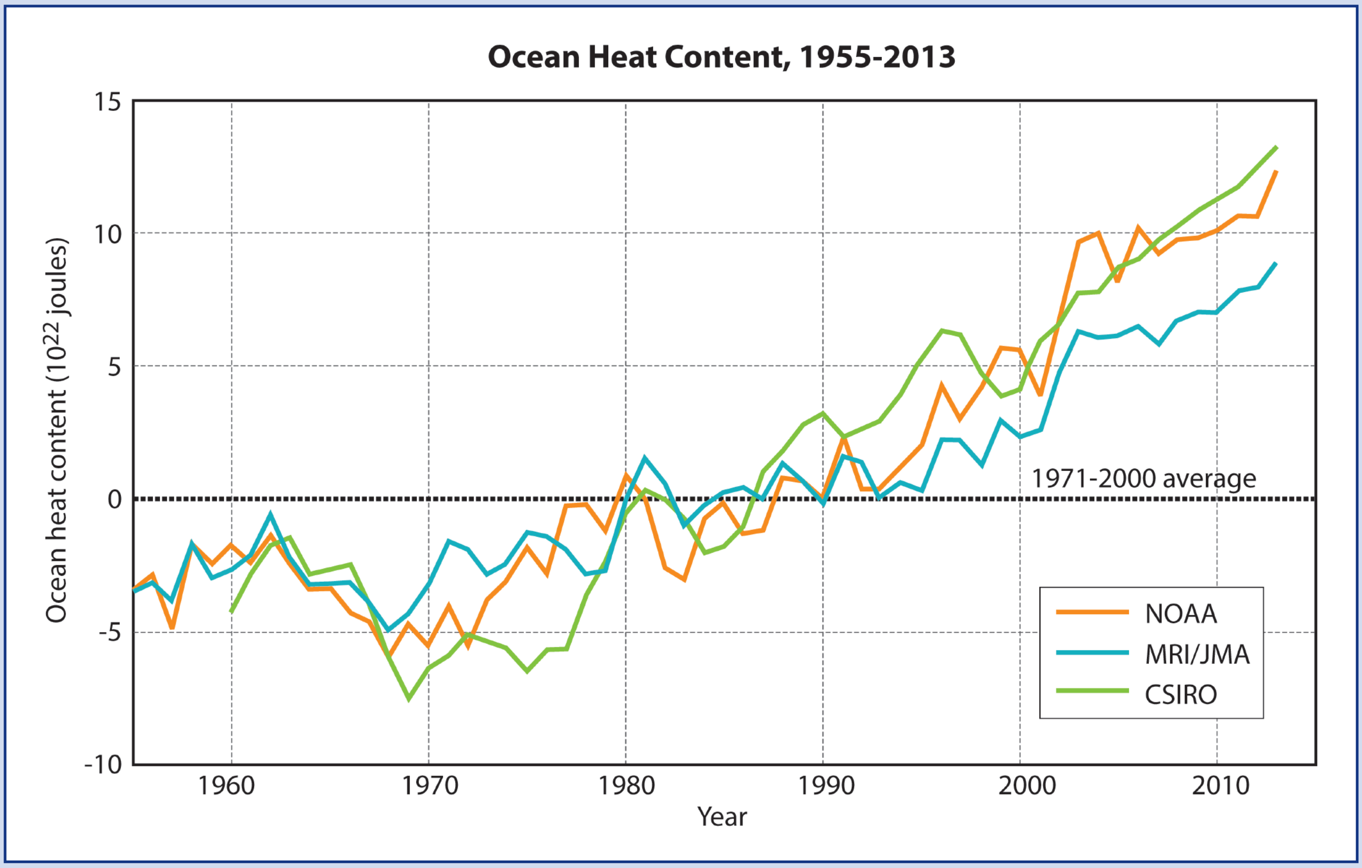


**Figure 7.4.** *Change in ocean heat content, 1960-2010. From http://www.epa.gov/climatechange/science/indicators/oceans/ocean-heat.html*

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# Acronyms

**AITP** Acoustic Ice Tethered Platforms
**AUTEC** Atlantic Undersea Test and Evaluation Center

**CEDA** Central Dredging Association
**CEEs** controlled exposure experiments
**CTBTO** Comprehensive Test Ban Treaty Organization
**CTD** conductivity-temperature-depth

**DMAC** data management and communication
**DOSITS** Discovery of Sound in the Sea project

**E&P** exploration and production
**EARs** Ecological Acoustic Recorders
**EIAs** Environmental Impact Assessments
**ESA** Endangered Species Act (U.S.)
**ESTOC** European Station for Time Series in the Ocean

**FOAM** Fast Ocean Atmosphere Model

**GC** glucocorticoid
**GOOS** Global Ocean Observing System

**HPA** hypothalamic–pituitary–adrenal
**HYCOM** Hybrid Coordinate Ocean Model
**IGY** International Geophysical Year
**IMO** International Maritime Organization
**IPO** International Project Office
**IPY** International Polar Year
**IQOE** International Quiet Ocean Experiment
**ISO** International Organization for Standardization
**IYQO** International Year of the Quiet Ocean

**MEPC** Marine Environmental Protection Committee (IMO)
**MMPA** Marine Mammal Protection Act (U.S.)
**MSFD** Marine Strategy Framework Directive

**NAVOCEANO** Naval Oceanographic Office (U.S.)
**NOAA** National Oceanic and Atmospheric Administration (U.S.)
**NRC** National Research Council (U.S.)
**NSL** noise spectral density level

**OGP-JIP** International Oil and Gas Producers-Joint Industry Program
**ONR** Office of Naval Research (U.S.)
**OOSs** ocean observing systems

**PAM** passive acoustic monitoring
**PAMBuoy** Passive Acoustic Monitoring Buoy
**PCAD** Population Consequences of Acoustic Disturbance
**PLOCAN** Oceanic Platform of the Canary Islands
**POGO** Partnership for Observation of the Global Oceans
**PSA** Particularly Sensitive Areas
**PTS** permanent threshold shift

**SC** Steering Committee
**SCOR** Scientific Committee on Oceanic Research
**SEL** sound exposure level
**SOFAR** Sound Fixing and Ranging
**SOSUS** Sound Surveillance System (U.S.)
**SPL** sound pressure level

**TTS** temporary threshold shift

# Appendix I
# Contributors to Science Plan

**Editors**
These individuals transformed the outputs from the IQOE Open Science Meeting into the Science Plan, based on experience with previous projects: Peter Tyack, George Frisk, Ian Boyd, Ed Urban, and Sophie Seeyave.

**Discussion Session Participants**
Most of the time at the IQOE Open Science Meeting was devoted to discussion sessions. Each group was led by two cochairs and two rapporteurs. These groups are responsible for the good ideas and much of the text in this Science Plan. The full list of participants is given in Appendix III.

**Theme 1:** Doug Cato and Manell Zakharia (chairs) and Christine Erbe and Tony Hawkins (rapporteurs).
Other contributors: Michael Ainslie, Caroline Carter, Ross Chapman, Thomas Folegot, Lars Kindermann, David Mann, Jeffrey Nystuen, Michael Porter, Mark Prior, and George Shillinger.

**Theme 2** (this theme was created from the outputs from two different discussion groups): Christopher Clark, Robert Gisiner, Vincent Janik and Jakob Tougaard (chairs) and Sophie Brasseur, Peter Evans, Roger Gentry, and Patrick Miller (rapporteurs).
Other contributors: Tomonari Akamatsu, Clara Amorim, Susannah Buchan, Dan Costa, Yong-Min Jiang, Darlene Ketten, Megan McKenna, Andy Radford, Steve Simpson, Peter Tyack, Michael Weise, and Rob Williams.

**Theme 3:** Brian Dushaw and Brandon Southall (chairs) and Rex Andrew and Jennifer Miksis-Olds (rapporteurs).
Other contributors: Michel Andre, Olaf Boebel, Del Dakin, Eric Delory, Richard Dewey, Albert Fischer, Lee Freitag, George Frisk, Tom Gross, Zygmunt Klusek, Fenghua Li, Ellen Livingston, David Moretti, Sophie Seeyave, Yvan Simard, Alexander Vedenev, Ed Urban, and Peter Worcester.

**Theme 4:** Frank Thomsen and John Young (chairs) and René Dekeling and Jason Gedamke (rapporteurs).
Other contributors: Hussein Alidina, Aurélien Carbonnière, David Farmer, Paul Holthus, Gail Scowcroft, Michael Stocker, Anne-Isabelle Vichot, and Dietrich Wittekind.

Others who did not attend the Open Science Meeting but contributed comments: Jesse Ausubel, Gerrit Blacquiere, Christ de Jong, and Bruce Howe.

# Appendix 2

# Matrix of Acoustic Capabilities of Existing Observing Systems

**Table 1** *(on three pages)* presents cabled systems.

**Table 2** *(on three pages)* presents fixed autonomous systems

**Table 3** *(on three pages)* presents mobile autonomous systems

***The following descriptions apply to the columns in the table:***

**Time synch/precision** relates to time synchrony between elements and between the GPS time.

**Data download** specifies the time interval between data downloads.

**Depth** is the depth at which the sensors are located.

**Calibration**" indicates whether or not the acoustic system is calibrated.

**Ancillary Data** highlights other data available or planned from the same region of the acoustic sensors.

**Data Availability** conveys how accessible the data are to the public.

**Sponsor** refers to the original and/or current sponsor providing funding support for the system.

**Society Value** indicates the societal purpose for which the system was originally designed

**Installation & Life Expectancy** reports the years of system installation and projected life expectancy of the system.

## Table 1 - Cabled Systems

| System | Geographical Scale | Location | Coordinates | Human Activity | Natural Activity | Projected Change | Acoustics Operational |
|---|---|---|---|---|---|---|---|
| CTBTO | basin | Wake Island | | | | | yes |
| | | Cape Leewin<br>Ascension<br>Diego Garcia<br>Juan Fernandez<br>Crozet Island | | low<br>low | | | yes<br>yes<br>yes<br>yes<br>yes |
| ALOHA | 100 km | Hawaii | | | | | yes |
| NEPTUNE | 100 km | Juan de Fuca British Columbia | | shipping | whales, geophysical | | yes |
| VENUS | 50 km | Strait of Georgia British Columbia | | shipping | whales, fish, geophysical | | yes |
| ANTARES | 50 km | Ligurian Sea | 43.0846N, 5.2115E | shipping, Navy, seismic | whales, geophysical | | yes |
| OBSEA | 10 km | Northwest Mediterranean Sea | 41.1819N, 1.7523E | shipping | whales, fish | | yes |
| NEMO | 25 km | East Sicily | 37.3211N, 15.3625E | shipping, Navy, seismic | whales, geophysical | | yes |
| JAMSTEC | 100 km | Hatsushima, Japan | 35.0031N, 139.2247E | shipping | whales | | yes |
| | 100 km<br>100 km<br>100 km | Kushiro 1, Japan<br>Kushiro 2, Japan<br>Kushiro 3, Japan | 41.6870N, 144.3945E<br>45.9408N, 145.0562E<br>49.2528N, 144.8107E | shipping<br>shipping<br>shipping | whales<br>whales<br>whales | | yes<br>yes<br>yes |
| | 50 km | DONET | | | | | yes |
| OOI RSN | 1000 km | Juan de Fuca Plate (Oregon/ Washington USA) | | shipping, fishing, some Navy | whales, odontocetes, pinnipeds, hydrothermal vents | climate changes in animal distributions possible | yes, but limited - opportunity for expanded capabilities |
| SOSUS | ~3000 km² | Northeast Pacific | various | shipping | whales | | yes/no |
| AUTEC | ~1250 km² | Bahamas | | military | beaked whale, odontocetes | | yes |
| SOCAL | ~1350 km² | Southern California | | military/shipping | beaked whale, odontocetes, mysticetes | | yes |
| PMRF | ~2500 km² | Hawaii | | military/shipping | beaked whale, odontocetes, mysticetes | | yes |
| PALAOA | 100s km | Antarctica | | low/none | whales, geophysical | | yes |
| ARGOMARINE | regional | Ligurian Sea | | shipping | | | yes |
| GOOS | | | | | | | no |
| IOOS | | | | | | | no |
| OOS | | | | | | | no |
| PLOCAN | coastal | Canary Islands | 27.9833N 15.3667W | ocean renewable energy, shipping | beaked whale, odontocetes, mysticetes | ocean renewable energy | none planned (2012-2013) |

## Table 1 - Cabled Systems (continued)

| System | Units (Auto) Mode (Mobile) | Frequency Bandwidth | Directionality | Time synch/ Precision | Duty Cycle | Data Downloads | # Elements | Depth | Calibrated |
|---|---|---|---|---|---|---|---|---|---|
| CTBTO | | <100 Hz | H | | continuous | continuous | 6 (2 triads) | sound channel | yes |
| | | <100 Hz<br><100 Hz<br><100 Hz<br><100 Hz<br><100 Hz | H<br>H<br>H<br>H<br>H | | continuous<br>continuous<br>continuous<br>continuous<br>continuous | continuous<br>continuous<br>continuous<br>continuous<br>continuous | 3 (1 triad)<br>6 (2 triads)<br>6 (2 triads)<br>6 (2 triads)<br>6 (2 triads) | sound channel<br>sound channel<br>sound channel<br>sound channel<br>sound channel | yes<br>yes<br>yes<br>yes<br>yes |
| ALOHA | | broadband | omni | | continuous | continuous | 1 | 4750 m (bottom) | yes |
| NEPTUNE | | 10 Hz-50 kHz hydrophones<br>1 - 200 Hz seismometers<br>360 s - 50 Hz seismometers | omni | ms in use<br>10 µs capable | continuous | continuous | 5<br>4<br>5 | 100-3000 m (bottom) | no |
| VENUS | | 10 Hz-50 kHz | H | ms | continuous | continuous | 9 | 100-300 m (bottom) | no |
| ANTARES | | 100 Hz-125 kHz | omni | ms | continuous | continuous | 36 | 2000 m (bottom) | yes |
| OBSEA | | 10 Hz-200 kHz | omni | ms | continuous | continuous | 1 | 20 m | yes |
| NEMO | | 10 Hz-96 kHz | omni | ms | continuous | continuous | 2 x 4 | 2500 m | yes |
| JAMSTEC | | 1-50 Hz | omni | ms | continuous | continuous | 1 | 2500 m | yes |
| | | 1-50 Hz<br>1-50 Hz<br>1-50 Hz | omni<br>omni<br>omni | msec<br>msec<br>msec | continuous<br>continuous<br>continuous | continuous<br>continuous<br>continuous | 1<br>1<br>1 | 2500 m<br>2500 m<br>2500 m | yes<br>yes<br>yes |
| | | | | | | | | | |
| OOI RSN | 7 planned nodes - each with seismic sensors and broadband phones | 5 Hz-1 kHz (seismic); 100 Hz-90 kHz (two overlapping broadband phones sampled 250 kHz) | omni | 1s | continuous | real-time (data transmission rate 10 kB/s) | notionally 7 nodes each with multiple sensors on each | variable (4 on shelf in 500-1000 m, 1 mid-plate in >3000 m and 2 on JdF Ridge in ~3000 m | yes - broadband phones |
| SOSUS | | 10 Hz - 500 Hz | omni | 1s | continuous | semi-annual | 1 | deep bottom, exact N/A | yes, legacy |
| AUTEC | | ~50 Hz-45 kHz | N | 500 µs | continuous | continuous | 91 | ~1200-2000 m | mixed |
| SOCAL | | ~50 Hz-45 kHz | N | 501 µs | continuous | continuous | 170 | ~1100-2500 m | mixed |
| PMRF | | ~50 Hz-45 kHz | N | 502 µs | continuous | continuous | 200 | ~150-4000 m | mixed |
| PALAOA | | 10 Hz-198 kHz | H | ms | continuous | continuous | 2 | 200 m | yes |
| ARGOMARINE | | 10 Hz-70 kHz | tetra array | | continuous | continuous | 4 | 20 m (bottom) | yes |
| GOOS | | | | | | | | | |
| IOOS | | | | | | | | | |
| OOS | | | | | | | | | |
| PLOCAN | | under definition | under definition | under definition | continuous | continuous | under definition | 100m | yes |

## Table 1 - Cabled Systems (continued)

| System | Ancillary Data | Data Available | Integration Possibility | Sponsor | Society Value | Installation Life Expectancy |
|---|---|---|---|---|---|---|
| CTBTO | no | approval needed | no | CTBTO | nuclear monitoring | early 2000s + decades |
| | no | approval needed | no | CTBTO | nuclear monitoring | early 2000s + decades |
| | no | approval needed | no | CTBTO | nuclear monitoring | early 2000s + decades |
| | no | approval needed | no | CTBTO | nuclear monitoring | early 2000s + decades |
| | no | approval needed | no | CTBTO | nuclear monitoring | early 2000s + decades |
| | no | approval needed | no | CTBTO | nuclear monitoring | early 2000s + decades |
| ALOHA | HOT site | open | yes | NSF | exploration | 2011 + decades |
| NEPTUNE | CTD, ADCP, echo, cameras, chemical, BPR, fluorometer | open | yes | CFI/Canada | ecosystems, biodiversity | 2009 + decades |
| VENUS | CTD, ADCP, echo, sediment, irradiance, fluorometer | open | yes | CFI/Canada | ecosystems, biodiversity | 2006 + decades |
| ANTARES | telescope | upon request | yes | ANTARES collaboration | Neutrino Observatory | 2000 + decades |
| OBSEA | CTD, video, meteorology | upon request | yes | UPC | meteorology | 2009 + decades |
| NEMO | HOT site | upon request | no | LFN/INGV | geo-hazards | 2005 + decades |
| JAMSTEC | seismometers | open | no | JAMSTEC | geo-hazards | 2005 + decades |
| | seismometers | open | no | JAMSTEC | geo-hazards | 2005 + decades |
| | seismometers | open | no | JAMSTEC | geo-hazards | 2005 + decades |
| | seismometers | open | no | JAMSTEC | geo-hazards | 2005 + decades |
| | | | | | | 2012 |
| OOI RSN | various oceanographic and geophysical | possible once operational (2013) | yes | NSF - OOI | ecosystem monitoring, research, education | 2011-12 laying cables; 2013 operational with possible additional acoustic elements later |
| SOSUS | no | TBD; request required | no | U.S. Navy / APL-UW | military | 1950s - ??? |
| AUTEC | SVP | screened upon request | yes | U.S. Navy | | >2020 |
| SOCAL | SVP | screened upon request | yes | U.S. Navy | | >2021 |
| PMRF | SVP | screened upon request | yes | U.S. Navy | | >2022 |
| PALAOA | CTD, video, meteorology | upon request | no | AWI | ecosystems, biodiversity | 2006 + decade |
| ARGOMARINE | compass | NATO countries | yes | NURC | communication, security | 2011 + decade |
| GOOS | | | | | | |
| IOOS | | | | | | |
| OOS | | | | | | |
| PLOCAN | | | | | | |

## Table 2 - Fixed Autonomous Systems

| System | Geographical Scale | Location | Coordinates | Human Activity | Natural Activity | Projected Change | Acoustics Operational |
|---|---|---|---|---|---|---|---|
| HAFOS | basin | Weddell Sea | | low/none | whale migration | no | yes |
| HARP | regional | Pacific Ocean, Atlantic Ocean, Gulf of Mexico, Gulf of Alaska, Hawaiian Islands, Chukchi Sea, etc. | 30 deployments, see http://cetus,ucsd.edu/projects_Main.htm | shipping, sonar, oil & gas exploration | marine mammals fish, ice, wind, rain, eathquakes | biological and human sound sources | yes |
| SBNMS | regional | SBNMS Arctic | | shipping | whales | | yes |
| EARS | regional | Ligurian Sea | | shipping | whales | | yes |
| NOAA EcoFOCI | regional | Bering Sea | | low | seasonal ice | climate, shipping, fishing | yes |
| | regional | Bering | | low | seasonal ice | climate, shipping, fishing | yes |
| PAL | regional | Station PAPA, Pacific Ocean | | low | | | yes |
| | regional | Ionian Sea | | shipping | whales | | yes |
| POI | 100 km | Sakhalin Island (Russia) | | oil exploration/ production | whales | increased industrial activity | yes |
| Hydra | regional | Ligurian Sea | | shipping | whales | | yes |
| IOPAS | regional | Baltic Sea | | shipping, oil platform | fish migrations | | yes |
| | | Spitsbergen Fjord | | shipping | diving birds | | yes |
| BIMET | coastal | N. Atlantic (Spain) | | shipping, geophysics | whales | | yes |
| SEAWAYS | regional | St. Lawrence Seaway | Lower St. Lawrence Estuary | shipping | whales | shipping | yes |
| ARCTIC-NET+ | regional | Eastern Beaufort Sea Canadian Archipelago Hudson Strait, Hudson Bay | | none to occasional shipping and airgun seismic | whales, Arctic marine life | climate, shipping, fishing | yes |
| PMEL | large scale | Pacific Ocean, Atlantic Ocean, Davis Strait | | | whales | climate, shipping | |
| DASAR | regional | Arctic Ocean | Beaufort Sea | oil & gas | whales | climate, shipping, fishing | |
| AURALs | regional | Arctic Ocean | Beaufort Sea, Chukchi Sea | oil & gas | whales | climate, shipping, fishing | |
| ESTOC-PLOCAN | regional | Central-Eastern Atlantic (ESTOC site) | 29.1667N, 15.3000W | shipping, volcanic tremor | whales (migratory and permanent) | | no, but planned |
| IMOS Perth Canyon | regional | Perth Canyon, Western Australia | | shipping, seismic surveys | whales | shipping, increase from whales | yes |
| IMOS Portland | regional | shelf break south Portland | | shipping, seismic surveys | whales, fish, ocean noise | | yes |
| IMOS NSW Australia | regional | shelf break west Cape Howe | | shipping | fish, whales | unknown | yes |
| IMOS Northwest WA | regional | northwest shelf, Western Australia | | shipping, seismic surveys | fish, whales | unknown | yes |
| JASCO-AMARs | regional | Chukchi Sea | 8-160 km offshore | oil & gas exploration | mysticetes, odontocetes, pinnipeds | | yes |
| ABB (SIO RAS) | regional | Black and Baltic seas | | climate, shipping, fishing | | | yes |
| AUSOMS | regional | Andaman Sea, Okinawa Island | | variable | variable | | yes |
| PAMBUOY | 100 to 100s kms | Sakhalin Island variable | n/a | shipping, oil platform, shipping, sonar, pile driving, seismic | whales and other marine mammals | biological and human sound sources | yes |

## Table 2 - Fixed Autonomous Systems (continued)

| System | Units (Auto) Mode (Mobile) | Frequency Bandwidth | Directionality | Time synch/ Precision | Duty Cycle | Data Downloads | # Elements | Depth | Calibrated |
|---|---|---|---|---|---|---|---|---|---|
| HAFOS | sonovault, AURAL, cPOD | 10-5000 Hz | omni | | continuous | 3 years | 10 | 850 m | no |
| HARP | bottom mounted, mooring, WaveGlider | 10 Hz-160 kHz | omni and 4-sensor directional array | 5-10 ms | continuous and programmable | 4-18 months | 1-4 sensors per deployment | 100-1000 m | yes |
| SBNMS | MARU | | | | | | | | yes |
| | | | | | | | | | |
| EARS | | 0-40 kHz | omni | | up to 50% | 40 days | 5 | 850 m | yes |
| NOAA EcoFOCI | PAL | 20 Hz-50 kHz | omni | 10s s | adaptive (2-5 min) | 6-12 months | 2 | 70 m | yes |
| | AURAL | | omni | | 16% | 6-12 months | 3-4 | 70 m | |
| PAL | | 20 Hz-50 kHz | omni | 10s s | adaptive (2-5 min) | 2 years | 1 | 500 m | yes |
| | | 20 Hz-50 kHz | omni | 10s s | adaptive (2-5 min) | 6 months | 1 | 500 m | yes |
| POI | AUR | 2 Hz - 15 kHz | omni | | continuous | weeks to months | 15-20 | 10 & 20 m (up to 100 m) | yes |
| Hydra | | 10 Hz-70 kHz | tetra array | | continuous | 53 days | 4 | 1000 m | yes |
| IOPAS | | 100 Hz-50 kHz | V, H | ms | adaptive | 6 months | up to 8 | 150 m | yes |
| | | 100 Hz-50 kHz | V, H | ms | adaptive | 6 months | up to 8 | 150 m | yes |
| BIMET | | 10 Hz-120 kHz | omni | ms | continuous | continuous | 1 | 100 m | yes |
| SEAWAYS | AURAL + cabled/shore | 1 Hz-100000 kHz | omni +H | µs to s | programmable to continuous | 3 to 12 months per year | up to 10 | 75-300 m | yes |
| ARCTIC-NET+ | AURALs | 1Hz-16 kHz | omni | s | programmable to continuous | 3 to 12 months per year | up to 8 | 50-250 m | yes |
| PMEL | PMEL autonomous hydrophone | | omni H | s | | | | | |
| DASAR | DASAR | 1-500 Hz | directional | | | | ~40 | 50-100 m | |
| AURALs | AURAL | 1 Hz-16 kHz | omni | | programmable | | ~30 | 50-100 m | |
| ESTOC-PLOCAN | under definition | under definition | under definition | under definition | under definition | 6 months | under definition | sound channel | |
| IMOS Perth Canyon | Curtin Univ. Loggers CMST-DSTO | 1 Hz - 6 kHz | omni | ms | 200 to 500 s / 900 s | 12 months | 4 | 430-500 m | yes |
| IMOS Portland | Curtin Univ. Loggers CMST-DSTO | 1 Hz - 6 kHz | omni | ms | 200 to 500 s / 900 s | 12 months | 4 | 130 - 160 m | yes |
| IMOS NSW Australia | Curtin Univ. Loggers CMST-DSTO | 1 Hz - 6 kHz | omni | ms | 200-500 s / 900 s | 12 months | 4 | 150-190 m | yes |
| IMOS Northwest WA | Curtin Univ. Loggers CMST-DSTO | 1 Hz - 6 kHz | omni | ms | 200-500 s / 900 s | 12 months | 4 + 2 | 250-300m | yes |
| JASCO-AMARs | JASCO-AMARs | 5 Hz - 8 kHz | omni & synchronised arrays | ms | continuous & 17% | every July & Oct | 35 AMARs & 9 AURALs | 20-50 m | yes |
| ABB (SIO RAS) | AURAL | 1 Hz-32 kHz | omni+V | ms | programmable and continuous | 3-4 months | 2 | 6000 m | yes |
| AUSOMS | bottom mounted and mooring | 20 Hz-22 kHz, max: 20 Hz-96 kHz | stereo | 22 µs | programmable and continuous | 15 days | 2 | 60 m | |
| PAMBUOY | | 10-150 Hz | omni | | continuous | continuous | 1 | 5-50 m | yes |

## Table 2 - Fixed Autonomous Systems (continued)

| System | Ancillary Data | Data Available | Integration Possibility | Sponsor | Society Value | Installation Life Expectancy |
|---|---|---|---|---|---|---|
| HAFOS | CTD, ADCP, echosounder | yes | yes | AWI | whale migration monitoring | 2011 + 10 yrs |
| HARP | CTD | upon request and approval | | Navy, NOAA, BP | marine mammals, ecosystem, shipping | 2005-2020 |
| SBNMS | | | | | | |
| | | | | | | |
| EARS | | NATO countries | yes | NURC | MMRM | 2011 |
| NOAA EcoFOCI | CTD, ADCP, echo, chl, oxygen, nutrients | yes | yes | ONR/PMEL | ecosystems, biodiversity | 2008 + 5 years |
| | CTD, ADCP, echo, chl, oxygen, nutrients | | yes | PMEL/NMML | ecosystems, biodiversity | 2008 + 5 years |
| PAL | meteorology, waves | yes | yes | NOAA | climate | 2006 + 5 years |
| | | yes | no | Poseidon | rainfall | 2008 + 5 years |
| POI | SVP measurements, current measurements | very limited | no | SEIC, ExxonMobile | industry monitoring | 2005 - deployed annually |
| Hydra | compass, tilt | NATO countries | yes | NURC | MMRM | 2011 |
| IOPAS | pressure, temperature, echo | upon request | yes | Polish national programs | exploration, weather, physical research | 2005 + decade |
| | pressure, temperature, echo | upon request | yes | Norwegian Funds | exploration, weather, physical research | 2006-2009, lost |
| BIMET | no | upon request | no | AZTI | MMRM | 2011 + decades |
| SEAWAYS | hydrography, ADCPs, hydroacoustics, circulation modeling | research program | yes | DFO UQAR | shipping MPA, marine park, whale watching | 2003 - + eventual permanent SEAWAYS observatory |
| ARCTIC-NET+ | oceanographic sensors, ADCPs, hydroacoustics | research programs | yes | Arctic-Net DFO UQAR | Arctic pre-industrial background, Inuit communities, climate change, ice melting, whale monitoring | 2003-2013+ |
| PMEL | | PMEL | | PMEL/NMML | earthquakes, whales, ocean basin | |
| DASAR | | oil & gas | | oil & gas | | 2008-2009 + |
| AURALs | | oil & gas | | oil & gas | | 2008-2009 + |
| ESTOC-PLOCAN | ESTOC station suite of instruments: including current, wind, salinity, CTD profiles, chl, oxygen, nutrients | data policy under definition | in progress | Spain Ministry of Science and Innovation and Canary Islands govt | exploration, weather, physical research | 1995 until 2025 |
| IMOS Perth Canyon | temperature | IMOS | | Australian govt | various | 2008-2013 |
| IMOS Portland | temperature | IMOS | | Australian govt | various | 2009-2013 |
| IMOS NSW Australia | temperature | IMOS | | Australian govt | various | 2010-2013 |
| IMOS Northwest WA | temperature & nearby oceanography | IMOS | | Western Australian govt | various | 2012-2014 |
| JASCO-AMARs | temperature | request approval | yes | Shell, Conoco Phillips, Statoil | marine mammal migration, distribution, density; baseline ambient noise | 2006-2016 |
| ABB (SIO RAS) | | upon request | yes | Russian Academy of Science | exploration, weather, physical research | 2003 + decade |
| AUSOMS | | | | | | |
| | | | | | | |

## Table 3 - Mobile Autonomous Systems

| System | Geographical Scale | Location | Coordinates | Human Activity | Natural Activity | Projected Change | Acoustics Operational |
|---|---|---|---|---|---|---|---|
| WaveGlider HARP | regional | Pacific Ocean, Atlantic Ocean, Gulf of Mexico, Gulf of Alaska, Hawaiian Islands, Chuckchi Sea, etc. | 30 existing deployments | shipping, sonar, oil & gas exploration | marine mammals, fish, ice, wind, rain, earthquakes | biological and human sources | yes |
| Argo | basin | global | | variable | variable | | no |
| AQARIUS | basin | global | | variable | variable | | yes |
| SPURS | basin | North Atlantic Ocean | | variable | variable | | yes |
| CPAM | local | Ligurian Sea | | shipping | whales | | yes |
| NURC-Gliders | regional | Ligurian Sea | | shipping | whales | | yes |
| PLOCAN-Gliders | basin | global | | shipping, volcanic tremor | whales | | no, but planned |

| System | Units (Auto) Mode (Mobile) | Frequency Bandwidth | Directionality | Time synch/ Precision | Duty Cycle | Data Downloads | # Elements | Depth | Calibrated |
|---|---|---|---|---|---|---|---|---|---|
| HARP | WaveGlider | 10 Hz-160 kHz | omni and 4-sensor directional array | 5-10 ms | continuous and programmable | 4-18 months | 1-4 sensors per deployment | 100-1000 m | yes |
| Argo | drifting | | | | | | | | |
| AQARIUS | drifting, Argo-like | 50 kHz | omni | ms | adaptive | 7-10 days | 45 | 1000 m | yes |
| SPURS | drifting, Argo-like | 50 kHz | omni | ms | adaptive | 7-10 days | 25 | 1000 m | yes |
| CPAM | towed | 20 Hz-80 kHz | | | continuous | continuous | 6 | 150 m | yes |
| NURC-Gliders | gliding | | | | | | | | |
| PLOCAN-Gliders | gliding | under definition | under definition | under definition | under definition | under definition | | 1000 m | |

| System | Ancillary Data | Data Available | Integration Possibility | Sponsor | Society Value | Installation Life Expectancy |
|---|---|---|---|---|---|---|
| HARP | CTD | upon request and approval | | Navy, NOAA, BP | marine mammals, ecosystems, shipping | 2005-2020 |
| Argo | CTD | | yes | | | |
| AQARIUS | CTD | open | no | NASA | water budget/ salinity/rainfall | 2011 + 2 |
| SPURS | CTD | open | no | NASA | water budget | 2012 |
| CPAM | pitch, roll, compass | NATO countries | yes | NURC | MMRM | 2011 |
| NURC-Gliders | | | | | | |
| PLOCAN-Gliders | CTD | data policy under definition | depending on system | Spanish Ministry of Science and Innovation | exploration, weather, physical research | 2011-2025 |

# Appendix 2
# Acronym Definitions

| | |
|---|---|
| **ADCP** | Acoustic Doppler Current Profiler |
| **ABB-SIO RAS** | Autonomous Bottom Buoys Shirshov Institute of Oceanology, Russian Academy of Sciences |
| **APL-UW** | Applied Physics Laboratory, University of Washington |
| **ARCTIC-NET+** | Network of Centres of Excellence of Canada to study the coastal Canadian Arctic |
| **ARGOMARINE** | Automated Oil Spill Recognition and Geopositioning Integrated in a Marine Monitoring Network (European Union Framework 7 Programme project |
| **ALOHA** | Cabled observatory 100 km north of Oahu, owned and operated by the University of Hawaii |
| **AMAR** | Advanced Multi-channel Acoustic Recorder (JASCO) |
| **ANTARES** | Astronomy with a Neutrino Telescope and Abyss environmental RESearch (an installation of the EuroSITES European Ocean Observatory Network |
| **AUR** | Autonomous Underwater Recorder |
| **AURALs** | Autonomous Underwater Recorder for Acoustic Listening |
| **AUSOMS** | automatic underwater sound monitoring systems |
| **AUTEC** | Atlantic Undersea Test and Evaluation Center (U.S. Navy) |
| **AWI** | Alfred-Wegener-Institut (Germany) |
| **AZTI** | an expert technology center in marine and food research |
| **BP** | British Petroleum |
| **BPR** | bottom pressure recorder |
| **CFI** | Canada Foundation for Innovation |
| **Chl** | chlorophyll |
| **CMST-DSTO** | Centre for Marine Science and Technology-Defense Science and Technology Organisation (Curtin University, Australia) |
| **CPAM** | compact passive acoustic monitor |
| **cPOD** | click detection and passive acoustic monitoring |
| **CTBTO** | Comprehensive Test Ban Treaty Organization |
| **CTD** | conductivity-temperature-depth |
| **DASAR** | Directional Autonomous Seafloor Acoustic Recorders |
| **DFO** | Department of Fisheries and Oceans (Canada) |
| **DONET** | Dense Oceanfloor Network for Earthquakes and Tsunamis |
| **EARS** | Ecological Acoustic Recorder |
| **ESTOC** | European Station for Time Series in the Ocean |
| **GOOS** | Global Ocean Observing System |
| **HAFOS** | Hybrid Arctic/Antarctic Float Observing System |
| **HARP** | High-frequency Acoustic Recording Packages |
| **HOT** | Hawaiian Ocean Time-series |
| **Hydra** | Acoustic telemetry service on the U.S. Pacific Coast |
| **IMOS** | Integrated Marine Observing System (Australia) |
| **IOOS** | Integrated Ocean Observing System (U.S.) |
| **IOPAS** | Institute of Oceanology, Polish Academy of Sciences |
| **JAMSTEC** | Japan Agency for Marine-Earth Science and Technology |
| **JdF Ridge** | Juan de Fuca Ridge |
| **LFN/INGV** | Low-Frequency Noise System of the Istituto Nazionale di Geofisica e Vulcanologia |
| **MARU** | marine acoustic recording unit |
| **MMRM** | marine mammal risk mitigation |
| **MPA** | marine protected area |
| **NASA** | National Aeronautics and Space Administration (U.S.) |
| **NATO** | North Atlantic Treaty Organization |
| **NEMO** | NEutrino Mediterranean Observatory |
| **NEPTUNE** | NorthEast Pacific Time-Series Undersea Networked Experiments |

**NMML** National Marine Mammal Laboratory (U.S.)
**NOAA** National Oceanic and Atmospheric Administration (U.S.)
**NOAA EcoFOCI** NOAA Ecosystems & Fisheries-Oceanography Coordinated Investigations
**NSF** National Science Foundation (U.S.)
**NSW** New South Wales (Australia)
**NURC** NATO Undersea Research Centre

**OBSEA** Expandable Seafloor Observatory (Spain)
**ONR** Office of Naval Research (U.S.)
**OOI** Ocean Observatories Initiative (U.S.)
**OOI RSN** OOI Regional Scale Nodes
**OOS** Ocean Observing System

**PAL** Passive Acoustic Listener
**PALAOA** Perennial Aco ustic Observatory in the Antarctic Ocean (AWI)
**PAMBuoy** Passive Acoustic Monitoring Buoy
**Station PAPA** Ocean Station P at 50°N, 145°W
**PLOCAN** Plataforma Oceánica de Canarias
**PMEL** Pacific Marine Environmental Laboratory (NOAA)
**PMRF** Pacific Missile Range Facility
**POI** Pacific Oceanological Institute

**SBNMS** Stellwagen Bank National Marine Sanctuary (U.S.)
**SEAWAYS** SEAWAYS Ocean Innovation (France)
**SEIC** Sakhalin Energy Investment Company
**SOCAL** Southern California Range Complex
**SOSUS** Sound Surveillance System (U.S.)
**SPURS** Salinity Processes in the Upper Ocean Regional Study
**SVP** sound velocity profile

**UPC** Universitat Politetécnica de Catalunya
**UQAR** Université du Québec à Rimouski (Canada)

**VENUS** Victoria Experimental Network Under the Sea (Canada)

**WA** Western Australia

# Appendix 3
# List of Participants

**Michael Ainslie**, TNO, NETHERLANDS
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