Science Plan

International Quiet Ocean Experiment
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Executive Summary¹

We will write this section after the other sections of the report have been reviewed by the OSM participants.

¹ The contributors to the Science Plan and their roles are given in Appendix II.
Introduction and overview

2.1 Purpose of the document

Underwater sound is important for many marine organisms. In general, marine species rely more on sound to support life functions than terrestrial organisms because the ocean is relatively opaque to light and transparent to sound. Ocean sound has many components, including naturally occurring sound sources 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-1800s, 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.** Examples of spectrograms showing different forms of sound in the ocean. (a) Sound from a ship where the vessel had been travelling at full power between intervals of power off; and (b) several different natural sounds. The intensity of the color represents sound intensity with darker color showing high intensity of sound.

Comment [EU1]: We will try to add a color bar to show the relationship between color and sound intensity.
Closely linked to the global economy (Frisk, 2007), the sound environment is changing quickly; additional sources related to naval activities, offshore construction, oil and gas exploration, fisheries and recreational boating now add to the mix. Intense sound can have acute impacts on animal life, but lower levels of continuous sound may lead to chronic effects, many of which will be difficult to detect. To the extent that human activities are steadily increasing ocean sound levels, it can be inferred that chronic effects will increase.

A scientific analysis of adverse effects from anthropogenic sound in the ocean is difficult because of the wide range of acoustical sources, variations in frequency, intensity and occurrence, and the complexity of acoustic propagation, especially in strongly stratified and shallow water. A realistic approach to understanding underwater sound and its effects on organisms requires new interdisciplinary and international collaboration, generally lacking in the past.

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 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, a Year of Ocean Acoustics (see Chapter 7).

2.2 Rationale for an IQOE

Does the sound made by humans harm marine life? At present, we can offer only preliminary answers to this important question, for only a few species. We know that the ocean has become more industrialized and that the sound levels associated with human activities have increased (NRC, 2003). For example, in areas where measurements have been made, anthropogenic sound in the ocean has been increasing across much of the frequency spectrum (Andrew et al., 2002; McDonald et al., 2008), and especially at lower frequencies (<500 Hz) (Frisk 2007, Andrew et al. 2011) (Figure 2.2). However, given the spatial and temporal complexity and variability in all sound sources, the relative contribution of anthropogenic sound is not always readily distinguishable.

The effect of sound on marine life is an important unknown of marine science. Considerable evidence has accumulated that the human contribution to ocean sound has increased during the past few decades; anthropogenic sound has become the dominant component of some marine soundscapes. Sound is an important factor in the lives of many marine organisms (Figure 2.3), and increasing theory and observations suggest that human sound could be approaching levels at which marine life may be experiencing chronic negative effects.

Some species show symptoms indicative of negative effects of sound. Although some of these effects are acute and rare in occurrence, chronic sub-lethal effects may be more prevalent, but are much more difficult to measure. We need to identify the thresholds of such effects for different species and be in a position to predict how increasing anthropogenic sound will increase the chronic effects. The IQOE is being developed with an objective of coordinating the international research community to both quantify the ocean soundscape and examine the functional relationship between sound and the viability of key marine organisms. This has implications for the stability and resilience of marine ecosystems and future marine productivity.
Figure 2.2. Historical and contemporary shipping traffic sound levels from Andrew et al. (2011). Solid lines represent the model fits 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 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).

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 non-profit organizations are more aware of the issue and can motivate action of various kinds, such as industrial guidelines 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 so as to foster rational discussion and public support for meaningful and justifiable action.

The basic scientific foundation for management of sound in the ocean falls into two related categories. First, the existing 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” which documents the changes in
atmospheric CO₂ concentration (Keeling, 1960) Documenting changes in the ocean sound environment will require long-term measurement with appropriate hydrophone arrays 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 exploit internal data recording, thus avoiding the need for long and expensive transmission cables, although existing systems such as hydrophones used for Comprehensive Test Ban Treaty verification would provide a helpful contribution. Underwater sound needs to be understood and modeled in terms of the different sound sources—both natural and anthropogenic—and the propagation characteristics that contribute to the building of a ‘soundscape’\(^2\). This will require development of comprehensive numerical models of ocean sound fields based on knowledge and measurements of the sources and of the propagation environment. Such 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.

\(^2\)A soundscape is a description of an acoustic environment.

\[\text{Figure 2.3.} \text{ The hearing ranges of different kinds of fish and mammals together with the overlap in frequency with different sources of man-made sound (from Boyd et al., 2011).}\]
sound this represents, by far, the most challenging aspect of the scientific and management problem. This challenge is unlikely to be resolved 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 deep ocean environment creates a sound channel by which low-frequency acoustic waves can be transmitted over large distances, sometimes hundreds of kilometers and often much further. The complex pathways taken by this sound affect the final received levels, but if they are averaged through time at the receiver they provide 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. It is sometimes possible to distinguish among different sound sources based on sound characteristics.

Humans introduce sound to the ocean through many different activities. Each source may have different effects, depending upon frequency range, its intensity and whether it is an intermittent, pulsed, or a continuous sound. Some anthropogenic sounds—such as some military sonar, seismic air guns used extensively for oil and gas exploration, and pile driving—are both impulsive and high intensity. These types of sounds can elicit strong negative reactions, or even physical injury, in some marine species. This concern 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 the stranding of beaked whales (Cox et al., 2006). Nevertheless, the acute effects of sonars upon beaked whales probably occur only rarely because the effects of sonars themselves co-vary with other factors, such as context of the exposure (i.e., bathymetry, presence of surface temperature ducts, behavior, and number of naval vessels). Animal strandings are probably the most easily observed end point of a syndrome of behavioral responses to sound in these species (Boyd et al., 2007), leading through some unknown progression to physical harm and/or mortality. There is a strong suspicion, supported by 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 (Stabbekoorn et al., 2010) and marine mammals (Southall et al., 2007; Tyack, 2008).

A major unanswered question in almost all of these cases is whether there is a significant impact on the fitness of individuals within populations that jeopardizes the viability of those populations. This was addressed by the U.S. National Research Council in its 2005 report on marine mammals and ocean sound (NRC, 2005), but the principles apply equally to all forms of marine life. The NRC report developed an approach known as Population Consequences of Acoustic Disturbance (PCAD) (Figure 2.4), which defines a rationale for developing assessments of the significance of sub-lethal 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 population effects—an essential requirement of this assessment process (Figure 2.5). Defining the transfer functions between the different boxes of the PCAD framework (Figures 2.4 and 2.5) 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 data sets derived from ongoing observational studies, passive acoustic monitoring, direct measurements, and the attachment of tags capable of measuring the received level of sound to marine organisms.

Shipping is 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 in
frequencies below 500 Hz. From 1950 to 2000, the shipping contribution to ambient sound increased by as much as 15 dB, corresponding to a rate of increase of approximately 3 dB per decade (Andrew et al., 2002, 2011; Frisk, 2007; Hildebrand, 2009). 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.

Many animals use sound in the ocean, either passively to listen and orient relative to their surroundings, or they actively produce sound themselves to search for prey or other objects, communicate, or in some cases as a by-product of other activity. The active use of sound is relatively easy to detect, but passive use is not. It is likely that most multi-cellular 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 propellers such as proposed for tidal turbines). 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, for some species, as the principal source of environmental information. Indeed, sound is so important for many species that understanding the acoustic environment amounts to describing the acoustic ecology of many species.

**Figure 2.4:** The Population Consequences of Acoustic Disturbance (PCAD) model developed by a committee of the National Research Council (2005). The arrows define transfer functions leading from the presence of a sound to its effects in ways that are 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.
Figure 2.5. A diagrammatic view of the issues being investigated by the IQOE (from Boyd et al., 2011). We define 3 major sources of sound in the ocean: physical, biological, and anthropogenic. The sounds involved in marine animal communication and echolocation can be “masked” by physical and other biological sound sources. Animal communication is likely to have evolved to cope with this type of masking. 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 that affect an animal’s ability to feed, migrate, and breed and which, in turn, may lead to changes in reproduction and survival of the individual. Relatively few responses at the level of physiology and behavior will have a direct effect on populations, but the effects of increasing levels of sound could accumulate across individuals, thus pushing these effects gradually from physiological and behavioral responses to population-level effects.

2.4 Defining the questions

Much evidence points to sound in the low frequencies (<10 kHz) being most important, 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 hear and, in some cases, produce complex sounds at much higher frequencies (up to >120 kHz in smaller cetaceans). Our basic knowledge of the way in which the majority of marine organisms sense sound and then respond behaviorally to different sound stimuli is quite rudimentary for most species and groups. Similarly, the extent to which higher background sound levels masks the ability of marine animals to interpret sound
signals from their environment is largely unknown, as is their reaction to 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., Miller et al., 2000; Foote et al., 2004; Holt et al., 2008; Parks et al., 2010). This 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 (Lengange, 2008; Slabberkoorn et al., 2008). There is evidence that, 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 ambient sound is of particular concern in low-frequency specialists, such as the large baleen whales (Clark et al., 2009). 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) are these general effects widespread among marine organisms, and (2) even if they are widespread, are they important to the function and survival of viable populations?

The IQOE will address the following major questions:

- What are the levels and distribution of anthropogenic sound in the ocean?
- What are the long-term trends in anthropogenic sound levels across the global ocean?
- What is the effect of anthropogenic sound on the viability of important marine animal populations?
- What were the global ocean sound levels before humans depleted sound-producing organisms and introduced sound from industrial, recreational, and naval activities?

2.5 IQOE objectives

The IQOE will last for 10 years. In very broad terms, the IQOE will test the hypothesis that there is an increasing level of man-made sound in the ocean and that this affects marine life in important ways. Because sound travels over ocean basin scales and because almost all human activities in the ocean generate sound in some way, simple calibrated measurement of sound over various time scales could be used to measure industrialization (Frisk, 2007). Consequently, over its duration IQOE will have the following objectives, which are described within the themes of this Science Plan:

1. To document changes in man-made sound in the ocean, including its distribution in space and time and to place this within the context of natural variations in sound;
2. To increase our understanding of the role that sound has within the global ocean, especially in terms of how it affects ecological structure and function;
3. To measure the effects of anthropogenic sound on key marine organisms, including the level of populations and communities to estimate the biological significance of anthropogenic sound; and
4. To develop approaches to observing the current state of sound within the global ocean and, through this, to hind-cast and forecast ocean sound at multiple spatial scales.
In parallel with researching these objectives we will build a sustainable, global scientific community with a critical mass of 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 goals will be achieved through the organization of four research themes:

**Theme 1: Ocean soundscapes**
- Characterization of soundscapes
- Identification of sound sources
- Modeling of soundscapes
- Trends in ocean sound
- Sound budgets
- Soundscape diversity

**Theme 2: Effects of sound on marine organisms**
- Experimental approaches
- Comparative and baseline studies
- Biological significance
- Measuring effects
- Determining dose-response relationships
- Model species
- Large-scale experiments

**Theme 3: Observing the physical and biological sound field**
- Data standards
- Global and regional observing systems
- Observing system integration
- New observing systems
- Biological observing systems
- Synthesis and modeling

**Theme 4: Scientific information needed for regulation of sound in the ocean**
- "Noise" monitoring and regulation
- Risk management
- Defining thresholds
- Measuring compliance
- Communicating results

The IQOE will develop an understanding of the current state of the ocean sound field, how this is changing because of human activity, and what effects this might have on marine life. It will also develop the capability to understand how ocean sound is evolving and how this may have affected marine life in the distant past and also into the future.

### 2.6 Anticipated benefits

The questions addressed by the IQOE are important for two main reasons. The first reason is that industrialization of the ocean is likely to increase in the next few decades. A very 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 further offshore into deep waters at continental shelf edges, at depths where sound can more easily enter the "deep sound channel."

Energy extraction from the ocean wind, waves, and tides—although relatively small 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. There are serious concerns that this process of increasing industrialization and recreation will lead us in small steps towards 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 and internationally. Reducing uncertainty by increasing our knowledge and understanding of the effects of human-generated sound on marine organisms will help avoid excessive regulation.

The second reason why we should give attention to the issue of sound in the ocean is even more profound and is one of concern to all responsible people. We are slow to learn the lessons from the negative impacts of the past industrialization of the ocean and that the dangers of causing irreversible declines in the quality of the planet’s self-regulating environment are tangible and real. We know that the non-linear, complex nature of the Earth system means that collapses could happen quickly and without much warning. At some point, small changes could lead to very large shifts in the state of the system. 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 we view it from a human perspective, as ecosystems that can no longer support normal goods and services, it has already happened locally as a result of direct exploitation (Bakun and Weeke, 2006; Thurstan and Roberts, 2010). The danger we face 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 biota. Unless we improve our knowledge of the consequences of sound pollution, we may be cruising blindly towards consequences that, in terms of a simple cost-benefit trade-off, could cost us much more than we will ever gain from ignoring them.

Therefore, the IQOE recognizes the benefits of its activities accruing across many stakeholder groups:

- **Regulators** who codify emerging legal frameworks as constraints on the sound radiated by industrial activity;
- **Legislators** who define the legal setting for sound and who respond to the public good;
- **Public** that has an increasing 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 targets and reference points to establish as objectives for managing anthropogenic sound in the ocean, and that have some objective foundation;
- **Scientists** because, while sound is usually overlooked as part of the physical structure of the ocean, it has such an important role within ocean biology that it is likely to have much more widespread importance than is currently appreciated. The importance of sound in the ocean has been appreciated by submariners 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.
2.7 Activities

2.7.1 Experimental approaches

To address the challenging questions posed by the effects of increasing ocean sound we need to ensure that science activities are coordinated across international boundaries and across disciplines. This is why an IQOE has been proposed. Such a project would employ two types of methods to help increase our understanding of sound in the ocean and its effects. One of these methods 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 to use planned lulls in sound production (e.g., due to planned shut-down of offshore construction, the diversion of shipping lanes, or the temporary presence and absence of sound sources). The second method will be to use opportunities to make observations in an unplanned or semi-planned experiment design, either through a comparative approach or an a posteriori opportunistic approach. These experimental approaches will require expanded observations and modeling.

2.7.2 Ocean soundscapes

A first step in this direction will be to define what we call ocean soundscapes. An ocean soundscape is a description of the acoustic environment that fully describes its spatial, temporal, and spectral content. Although we have identified at least 30 sites or networks globally that have currently or recently collected data about ocean sound (see Appendix 1), 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), data for wind and rainfall, and data for seismic surveying, sonars, and pile driving—may provide a general view of the sound fields across the global ocean. The biggest “unknown” in estimating the global soundscape will 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 this model 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 Global Ocean Acoustic Observing System (e.g., Dushaw et al., 2009). This system will build on the existing and planned capability of the Global Ocean Observing System, and local and regional systems such as the U.S. Integrated Ocean Observing System and the Australia 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.

2.7.3 Predicting Sound Fields and Managing Sound Inventories

Establishing the global ocean soundscape, with appropriate statistical characterization of its variation in space, time, and frequency, is a necessary step towards predicting ocean sound fields in particular locations. These predictions can then be challenged with the in 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.
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 production, principally on a precautionary basis. But existing information is not sufficient to build the rationale for spatial management of industrial activities in order to reduce potential sound impacts on sensitive species or habitats. The development of sound budgets 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 be able to set legally binding conditions on use of the ocean. This nested approach to model development and validation is necessary because sound is a problem that needs to be tackled initially at large scales because of the long-range propagation of low-frequency sound. Even local models need to have the boundary conditions specified in order to build local sound budgets and we intend to provide this capability.

2.7.4 Exploration in Deep Time

What was the global ocean like before humans arrived? 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 pre-industrial era? Similarly, can we predict the ocean soundscape in the future if current trends continue? 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.

The challenge and opportunity of the IQOE is to coordinate scientific activities on the effects of ocean sound on marine organisms internationally, whether conducted in the academic, governmental, or industrial (e.g., Joint Industry Program) sectors. The development of a body of knowledge that begins to flesh out the types of responses to different levels of sound in the life functions of individual organisms—such as changes in the reproductive rate, growth rate, use of habitat, survival rate and 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 will need to 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, such as the PCAD model referred to previously.

Sound budgets are defined as the overall distribution of sound energy at a particular location within a defined period of time.
3.1 Characterization of Soundscapes

Quantitative description of the ocean sound field, which is how we define soundscapes, is fundamental to any analysis of the trends in 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 the mean and variance of the sound field, spatially temporally, and with respect to the frequency. The term *soundscape* used in the context of the ocean has resonance with a landscape because whereas light is the principal source of environmental information within landscapes, sound takes precedence within the aquatic environment. Our ability to perceive the land and the ocean reflect our ability to sense light and sound, respectively. Indeed, both have the same level of spatial and temporal dynamics.

The term *soundscape* has developed recently within the terrestrial environment (Pijanowski et al. 2011). 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, here we intend to provide a view of the ocean sound field and how it varies that is independent of the characteristics of the receiver. For example, the acoustic environment of two co-located organisms that have different capacities for sound perception could be very different, but both experience identical soundscapes. We need to be careful to ensure these are distinct concepts.

The variation in sound, which is really what the soundscape describes, 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 serendipitous changes in the soundscape. 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 place and time, a soundscape may be described quantitatively in terms of different measures such as

- the acoustic waveform as a function of time (which contains all the information about the sound sources in the soundscape);
- 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 exposure 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 one month. However, 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 extremely difficult to independently verify the interpretations given in such figures, which rely on the experience of the observer. Spectrograms of this type often contain sounds for which there is no obvious explanation.
The variation in the soundscape represented by the section in Figure 3.1 is remarkable, and 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. Note that in this case the spectrum ranges from 10 Hz to about 20 kHz and the soundscape could contain high energy below 10 Hz representing the pulsing beat of ship propellers. Many marine mammals also use frequencies >20 kHz, but the propagation of sound to long ranges at these higher frequencies is much less effective than at the lower end of the spectrum of sound in water. This frequency-dependent attenuation means that the spatial scale reflected in a spectrogram of the type provided by Figure 3.1 changes from small scale (a few kilometers) at the top of the diagram to a very large scale of hundreds of kilometers at the bottom. Soundscape analysis aims to present the distribution of acoustic energy at a single spatial scale.

Characterization of the soundscape can be tackled from two opposing directions, each of which should ideally lead to a convergent result. The directions represent the derivation of soundscapes based upon (1) empirical observation of isolated sections through soundscapes, as illustrated by Figure 3.1, and stitching together many of these across required spatial scales, and (2) observation of the sound sources and the derivation of a sound field by modeling the propagation of sound from these sources.

Figure 3.1: Spectrogram of a soundscape including snapping shrimp (pink box), evening fish choruses (white ellipses, only drawn for four nights), nearby humpback whales (red ellipses) and distant humpback whales (red box), and a distant seismic survey (yellow box). The thin grey boxes at low frequencies highlight sound from fluid flow around the recorder. This is an artifact of measurement and is not considered part of the soundscape. Source?

Both these approaches have strengths and weaknesses that are expanded on later in this Science Plan but, because they are independent of one another, they present an opportunity to provide independent validation. Soundscape descriptions are most often derived from modeling sound sources using propagation models (i.e. the second approach described above). Consequently, to provide validation there would be a need in these circumstances to
use this approach to predict the amplitudes of sound within the kind of soundscape sections illustrated by Figure 3.1 and then compare the prediction with the actual soundscape section. Thus the IQOE has an opportunity to test and improve sound propagation models. This approach was adopted during the ATOC (Acoustic Tomography of Ocean Climate), experiment that ended in 2006 (Munk and Wunsch, 1983; Munk et al., 1994). Based upon a known sound source located close to Heard Island in the southern Indian Ocean, this experiment made use of the idea that if one knows the sound source characteristics, and can differentiate the sound from other sounds in the ocean, and one controls the position of the receiver, then the way in which the sound is modified between the source and the receiver is indicative of the properties of the water through which the sound has travelled (Munk et al., 1994). This includes the temperature of the ocean and the ATOC experiment was designed to examine long-term changes in temperature at whole-ocean scales. However, ATOC was an approach that measured a defined sound signal at a receiver. This design could be generalized to validate sound propagation models or, more likely, to define the general level of uncertainty in these models, both of which are tools for predicting soundscapes.

This kind of validation process would most likely only be appropriate at low frequencies. As described for Figure 3.1, the spatial range represented by the spectrogram of the cross-section of the soundscape is progressively biased towards sources closer to the receiver as frequency increases. Consequently, the frequencies available for validation will depend upon the spatial scales at which the propagation modeling can be carried out. Indeed, the ATOC experiment had a frequency centered on 75 Hz.

Sound levels are usually determined by measuring pressure and this is largely what has been considered so far, but fish and invertebrates also sense particle velocity representing the actual motions of fluid elements in response to the fluctuating pressure of the sound field. The particle velocity has a directional component depending on the principle direction in which the sound is propagating. Hence, methods of measuring or estimating particle velocity need to be included to characterize soundscapes. Directionality of sound can also be sensed by marine animals, so this variable needs to be understood when including marine mammal vocalizations within soundscapes. 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.

The complete characterization of the ocean soundscape using propagation modeling can only be achieved to within certain bounds of accuracy. Ideally, we desire to have the capacity to predict the sound spectrum in any particular part of the three-dimensional ocean at the finest possible scales. However, there are several major classes of constraint. These constraints include the scale at which other relevant data are available, such as bathymetry, and temperature and salinity profiles that dictate sound speed at different depths. Other limitations exist because of fundamental inaccuracies within sound propagation models themselves, which are necessarily approximations of the physics involved in sound propagation, and many of these limitations will co-vary with the scarcity of data that are used to provide inputs to these models. However, perhaps the greatest constraint comes from information about the distribution, abundance and characteristics of sound sources.

**Key Questions**

Relevant questions related to the characterization of soundscapes include:

- What physical 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 with particular characteristics. The most productive approach to increasing knowledge of soundscapes would be to develop a framework for calculating the soundscape. 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 carefully structure the approach to allow progress to be made within the current constraints of the data.

We will use a nested approach by first focusing on the large, global or ocean-basin scale with relatively coarse spatial grids so that this can be used to define the boundary conditions for calculations of the soundscape at regional and local scales, both of which may be able to use much smaller grid sizes. Models to describe sound propagation and the oceanography to determine sound speed are both available at the large scale. In some specific places, regional and local characterizations of the soundscape will also be possible because of the quality of the data available.

The global-scale characterization will use global approximations for oceanic conditions, including seasonal variation and using the kind of grid sizes commonly applied on global oceanographic data sets. Data sets that have similar levels of accuracy are available for the three additional layers required to describe a global soundscape, namely, (1) weather as a physical sound source, using global weather charts; (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.

Initial versions of the implementation of this global soundscape calculation will produce highly uncertain outputs but will create a clearer view of where the greatest uncertainties lie and the most effective way in which uncertainty can be reduced. Early implementation of soundscape characterization is vital to define those variables that lead to the greatest uncertainty because it is important to focus, in the remainder of the IQOE, on assimilating and/or collecting the data that will contribute most to the reduction of variance in soundscape calculations, much of which will be delivered through Theme 3 on Ocean Observation.

The output from this work will be an ocean sound 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 this will consider the integrated total power (integrated across frequency and depth) at a particular location in the ocean.

Future iterations of the global soundscape characterization will include variations based upon different scenarios associated with the physical, biological and anthropogenic data layers. Three example scenarios that will be explored are:

1. The outputs from global circulation models and long-term weather prediction will be used to examine the impact of climate change on ocean ambient sound from weather and the way in which changes in ocean stratification may affect the intensity of ocean sound in particular regions.
2. Changing the biological layers to those more representative of a pre-fishing and pre-whaling era 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 break-up of Antarctic ice sheets) and increasing industrialization of the ocean.

Ambient sound is the term used to describe background sounds that merge in such a way that their individual sources cannot be distinguished. Consequently, the level of ambient sound is a function of several factors, including the number and bandwidth of sound sources and their range from the detector. If different sound sources overlap in terms of 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 these different sources. Figure 3.2 shows this pattern of complexity involving overlapping sound sources.

Finally, an aspiration is to make soundscape characterization the center-piece of the assessment of the global trends in ambient sound. This is only aspirational at this stage because of the immense amount of work required before this can be achieved. For the immediate future the development of assessments of global trends in ambient sound need 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 near-field transient sound sources, it is difficult to compile an authoritative view of whether ambient sound is increasing. Soundscape characterization is one approach that can integrate data from many sources—physical, biological, human—to examine trends in sound based upon 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 sparse observations. This approach has the potential to provide 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. 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.

3.2 Ambient sound and the components of soundscapes

Ocean soundscapes are composed of a combination of ambient sound and sounds from sources that can be localized, which 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 sound is typically used as a surrogate for a spectrogram of a sound field in which there are no specific identifiable sources.

Ambient sound (often referred to as ambient noise in the published literature) includes sound from the sea surface, sound from distant shipping (defined as traffic sound) and biological choruses when animals are so numerous that the sounds of individuals merge into a continuous background. Localized individual sources include passing ships, other anthropogenic 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 and an example of the sound spectrum from pile driving is given in Figure 3.3.
The natural components can be further sub-divided into the physical sound sources such as from weather or ice and the biological sources such as from snapping shrimp, fish and whales.

Ambient sound has been studied extensively for about 70 years so that we have substantial knowledge on the characteristics of ambient sound in general, and in many environments in particular. Historically, most of the measurements of ambient sound have been motivated by naval strategic 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 lower or very little human activity, although there has been some work around Australia, New Zealand and the Antarctic.

Ambient sound variation with weather conditions can form a substantial component of the background sound field (Figure 3.2). However, wind speed can be used as a proxy for ambient sound. Figure 3.4 shows 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. As shown by the figure, the relationship shows a consistent and linear pattern, raising the possibility that surface wind speed data can be easily 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 3.2:** Summary of ambient sound spectral 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 shrimps in shallow water (modified from Cato, 1997).
Temporal variation in ambient sound is substantial, typically around 20 dB re 1 uPa @ 1 m due to variation in weather and biological activity, with extremes of variation in excess of 30 dB re 1 uPa @ 1 m. 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, continuous and transient, near-by and distant sources 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.

However, it is also important to understand why ambient sound varies through time and as well as variations in the wavelength of the kind of variation in the kind of ambient sound profile illustrated in Figure 3.3 can provide clues about this source of sound and, consequently, allow a certain amount of dis-entanglement 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). Similarly strong seasonal trends in ambient sound in particular frequencies have been observed by the hydrophones deployed by the Comprehensive Test Ban Treaty Organisation (CTBTO) in the Indian Ocean and these are most likely to have been associated with whale migrations. Annual changes with specific timings may also be related to weather.

Figure 3.3. The average 1/3-octave band spectra of the sound exposure level (SEL) at two different distances from the piling, compared with the SEL of the average environmental noise. De Jong & Ainslie (2008).
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, spectral or statistical (or a combination). It is important to appreciate the physical mobility and statistical non-stationarity of most of the sources of interest (at various scales) that often lead to using non-stationary descriptors such as spectrograms, in spite of their shortcomings.

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

![Figure 3.4. Ambient sound level (NSL) in relation to wind speed. 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).](image)

Nevertheless, in spite of the importance of localized sources importance for the characterization of soundscapes, most practical circumstances 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 has attracted a large amount of attention in the past because of the importance of localized sound sources in military applications for detecting the signal of a submerged object from within the background ambient sound. 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, wave height, sound velocity profiles, and ocean bathymetry and sediment type.

It will be challenging to design systems that classify sound sources based upon all available a priori information that could help in resolving the problem, such as oceanographic

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measurements, visual observations, ship tracks from the Automatic Identification System (AIS), information about the presence of other industrial activities such as pile driving or seismic surveying. Access to historical data will 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. PAMGUARD (http://www.pamguard.org/home.shtml) has been designed as an open-source software tool that can be downloaded free and that software designers can add to. Its development was sponsored by the oil and gas industry to promote the development of a satisfactory system for detecting, localizing and classifying marine mammal sounds during seismic surveys. However, its open source architecture means that individuals can design detectors for any sound source and load them into PAMGUARD, allowing this software tool, and improvements made to it by any member of the research community, to be available to all researchers. PAMGUARD can operate in real time or as a post-hoc system for analyzing detections using WAV files.

Figure 3.5: Temporal variability of sound recorded over a 3-week-period off the Queensland coast. The nth percentile gives the level that was exceeded n% of the time. The recorder was deployed in 10m deep water, 500m from a shark net with pingers operating at 3 and 10 KHz and 10 km from a sand pump (Erbe et al., 2011).
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?
- Are there important sound sources for which we have insufficient information about both the sounds they produce and their distribution?
- Are there patterns in the behavior of sound sources that might be important to help predict the underlying causes of ambient sound variation?

Figure 3.6: The IQOE will estimate the contribution made to ambient sound by the breakup of Arctic ice floes.

Research approach

The number and type of potential sound sources are almost limitless, making it impractical to include every individual source in models to produce estimated 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 and/or densities of individuals. 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 and human. 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.

In the case of 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, especially in the Arctic, is that associated with ice 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 which dependent upon the larger scale current and wind stresses. The closing of winter leads also produces a distinctive sound. Interaction of ice-floes in the marginal ice zone is affected by wind and waves and the source of significant sound. An important source of sound, especially in the Southern Ocean, is that generated by calving icebergs and the progressive failure of these as they break up.

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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/) that has already been created.

Furthermore, we will support the continuation of an extant, but ad hoc, Detection-Classification-Localization (DCL) Working Group, including researchers with a common interest in the detection and classification of marine biological sound, especially from marine mammals. In this context, we will also support the further development of PAMGUARD as an appropriate software system for data collection and off-line analysis.

**Figure 3.7:** Examples of biotic contributors to ocean sound.

### 3.3 Modeling soundscapes (Sources and Propagation)

Ocean soundscapes are characterized in a variety of different ways. In many cases biologists 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). 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.

Significant effort has been devoted to developing sound propagation models over the years, mainly for naval applications. However, much of this work has focused on detecting extremely quiet sources (submarines) by listening to 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 upon 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 2-dimensional slices radiating away from the sound source. As sound encounters different discontinuities, such as the surface, the sea bed 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 the salinity changes with depth are, therefore, 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 conditions; (3) water depth or bottom topography; and (4) geoacoustic sub-bottom structure in terms of the 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, similar to light waves.

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

Probably the biggest challenge in this process is to model the ocean bottom reflectivity accurately. Some limited global databases are available. Interestingly, it may be possible to ‘bootstrap’—as we learn more about key sound sources, such as shipping traffic, ships may be seen as beacons that ‘illuminate’ the environment. Their brightness as they crisscross the global ocean is itself a measure of the reflectivity of the ocean bottom. Exploiting this information to provide information about the structure of the ocean, as was the case in the ATOC experiments (see section 3.1) is an interesting challenge for the IQOE.

Overall, there will be a need to develop approaches to modeling that use approximations for information required. For example, we are uncertain how critical precise variability in oceanic conditions will be for the investigations of general questions at large spatial scales or whether approximations over large space and time scales may suffice. Similarly, it may be that functional relationships between ocean sound and wind speed may provide an appropriate surrogate for ocean weather (see section 3.2). Consequently, any modeling will need to be explicit about the scales over which it is operating and about the uncertainties involved.

Modeling the propagation of sound for the purpose of characterizing 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 2D vertical slice. The IQOE will encourage the development of modern advances in 3D sound propagation modeling (Fig. 3.8).

By making several broad assumptions, it should be relatively easy to generate soundscapes 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.
Figure 3.8: Rays of sound travelling over a complicated topography that produces three-dimensional (out of plane) effects.

To reduce the discrepancy between the scales at which soundscape models are likely to be developed and those associated with data collection, validation may most likely succeed initially at lower frequencies because the measurement of low frequencies at single points where observations are made are likely to be most representative of larger spatial and temporal scales. Validation will become more complex with increasing frequency.

Model validation may be possible by fitting the model results to observation data. Since the models themselves can be generated independently of the observation data, 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 are 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 out 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. This is essentially a 1000 km square cave well isolated from anthropogenic sources of sound and that has its entrance pointing toward the South Pacific and South Atlantic oceans.
Key Questions

Relevant questions related to modeling soundscapes include the following:

- To what extent can current models be used to characterize soundscapes and be explicit about 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)?

Research approach

Ensemble modeling, the use of multiple models to evaluate specific scenarios, will be used to examine the influence of model structure and assumptions. 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. This model validation may be carried out in conjunction with other studies in the Experimental Approaches and the Ocean Observations 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.

The IQOE also wishes to support the development of new models that include 3-D capability and that are dynamically linked to oceanographic models (Theme 3), as a way of developing improved real-time model certainty.
Theme 2: Defining the effects of sound on marine organisms

4.1 Introduction

This theme describes the IQOE approaches to studying the responses of marine organisms to their acoustic environments, including human-induced changes in ocean soundscapes. This concerns the interaction between organisms and their environment and is also, therefore, about the acoustic ecology of marine organisms. There are two distinctive approaches to examining this problem: (1) using opportunities to make observations in an unplanned or semi-planned experimental design and (2) the use of planned experiments. This theme will deal with these two approaches separately, although there is some overlap.

However, before considering these approaches to addressing the question of how sound affects marine organisms, there is a need to consider how soundscapes—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 upon what organisms hear and how they hear.

Relatively little is known about the effects of anthropogenic sound on marine organisms, in relation to what we need to know. Popper and Hastings (2009) reviewed the literature for fish and concluded that very 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. It is debatable as to whether any more is known about effects of sound on marine mammals (Southall et al. 2008). In this case, some acute effects are known (e.g., Cox et al. 2006) but, overall, the effects of masking of communication by anthropogenic sound, disturbance by sound, or the direct physical effects of sound are poorly understood. In theory, we expect a dose-response relationship like the one illustrated in Figure 4.1. In this particular case the 50% probability of harassment has been defined as happening at a sound exposure level of 165 dB re. 1 µPa @ 1 m. The derivation of these types of relationships is central to examining the effects of anthropogenic sound on marine organisms. For example, recent analysis of beaked whale responses to sonar and other pulsed sound has suggested a response in the region of 140 dB re. 1 µPa @ 1 m. In these circumstances, we might expect a dose-response relationship more like the blue curve illustrated in Figure 4.1.

In some cases, responses are defined by physiological criteria, such as permanent or temporary threshold shifts (Southall et al. 2008), but behavioral thresholds, such as the blue curve for beaked whales, are becoming increasingly 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 such response functions. Similarly, although Figure 4.1 shows “harassment” as the response criterion, many other criteria could be used; established 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).
Consequently, a priority for the IQOE will be to better define the response functions for key species, especially keystone species within ecosystems, commercially important species, and species of conservation concern.

Figure 4.1 The dose-response relationship used by the U.S. Navy to define the threshold for harassment of odontocete cetaceans (red, excluding harbor porpoises and beaked whales) and a dose-response function defining a lower threshold that may be more realistic for beaked whales (blue).

4.2 Acoustic environments

Theme 1 will deliver a comprehensive description of soundscapes and, while this will help to predict the sound environment that any organism is exposed to at any specific place and time, it does not define what an organism may hear and, therefore, how it may respond. The hearing thresholds of marine organisms (Fig. 4.2) are not well 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, significant uncertainties remain regarding the diversity of frequency-dependence of hearing capability, as well as hearing sensitivity, in many species. Fish detect particle motion as well as sound pressure (Popper and Fay 2011), and there is relatively little understanding of hearing capabilities in invertebrates. 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. 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).

Sounds generated by human activities have changed in many marine environments, and continue to modify the acoustic habitats of many marine species and may affect ecological interactions. The acute, short-term impacts and chronic long-term influences of these changes at biologically meaningful spatio-temporal-spectral scales are poorly understood, but there is increasing evidence that animals are responding to and behaviorally compensating for influences from anthropogenic sounds (refs.). The relative risks of these different effects at either individual or population levels can be partially constrained by relating the dynamics of the physical acoustic field (i.e., the soundscape) to which animals are exposed with the bioacoustical functions of a species’ acoustic signals (e.g., communication, navigation, foraging) and its auditory perception capabilities (e.g., sensitivity, thresholds). In some cases these changes could have a direct and acute impact on an
individual (e.g., a beaked whale responding to mid-frequency sonar, Tyack et al. 2011) or more of an indirect and long-term influence on a population (e.g., prolonged and large-scale reduction in communication space for northern right whales, reduction in foraging efficiency in resident killer whales, Williams and Ashe 2007).

![Graph showing hearing thresholds for different organisms](image)

**Figure 4.2** Stylized examples of the hearing thresholds (audiograms) of a range of marine organisms.

Sound production by human activities becomes biologically significant to an individual animal when it affects an individual's survival or ability to reproduce. Such effects on individuals can then cascade into population-level consequences and impact the function of ecosystems. A characteristic of the problems concerning the effects of sound in the ocean is that it modifies the acoustic habitats and acoustic ecosystems of a broad suite of species, thus amplifying the ecosystem risk and complicating our ability to detect cause-and-effect relationships. This becomes especially difficult when considering that the largest ocean acoustic habitat modifications are likely to be occurring in the low-frequency range (<1000 Hz), over large ocean areas (e.g., 100,000 nm²) and for long periods of time (e.g., annually for many months to decades).

Consequently, acoustic environments of different organisms, even if they are co-located, could be very different and this is important when examining the consequences of sound. Sound at particular frequencies has the potential to elicit widely varying responses from organisms and to change community dynamics in ways that are much greater than simple dose-response relationships might suggest. This is because of the potential for sound to cause uneven effects on organisms at the community level. In some circumstances, changing the competitive balance among species can result in cascade effects within communities (Ruttenberg et al. 2011).
Overall, therefore, there is a need for more research focused on how marine organisms sense sound and the variation in acoustic sensitivity among species, as well as the range of sensitivity within individual species and how changes in sound affect interactions among individuals.

4.3 Unplanned or semi-planned experiments

Ethical and practical constraints often make it difficult to carry out precisely planned experiments on the effects of sound on marine life. Indeed, any experiment conducted in the field is likely to be more or less of the semi-planned variety 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, very small numbers of individuals and species are available for study. This can result in biased results because it is impossible to control for individual variation, inter-species differences, and/or serial correlation within experiments.

We define two main forms of unplanned or semi-planned experimental approach. One, termed 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 non-captive, non-agricultural species. The other 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 experimental 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 methods (e.g., Bayesian techniques) are used to separate the signal in the data from noise associated with effects from uncontrolled variables.4

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; and
3. Post-effects monitoring: documenting the return of the organisms to their original state after the period of anthropogenic sound production.

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4 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.
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 assessment of effects that result from acoustic stress 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. However, more often, 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.

Opportunistic approach

This 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* 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.

Baseline studies

Baseline studies provide a quantitative assessment of the normal, undisturbed state of organisms, communities, social structures or 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. Higher statistical power to detect changes can be obtained by either extending the duration of the baseline or by measuring a broad range of co-variates alongside the baseline. These co-variates could include other potential anthropogenic stressors that may change during the course of the study, but may also include indicators of the physical and biological system. Including these 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, in effect, controls for the “noise” effects of the co-variates 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 does not mean it is not biologically significant and, conversely, even if a signal is detected this does not mean it is biologically significant.

We expect that the IQOE will include many studies of this type. Most will be characterized by some form of observation associated with some form of 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 (see Figure 4.3) often collecting and processing 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.
Measuring effects using quieting

The origins of the IQOE were based on the idea that, rather than introducing additional sound and observing the effects of this, there was a need to examine the responses of organisms to quieting. Comparative and semi-unplanned approaches provide an opportunity to make progress with this ambition.

By using variation in the background sound levels, including intermittent noisy and quiet periods, it is possible to examine responses to the full range of sound levels and types (e.g. chronic or acute conditions). This is as much about responses to quiet conditions as it is about the opposite. Statistical models applied to these data can then be used to predict the effects of reduction in noise.

Measuring rare effects

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 acute effects of sound exposure can be classified as rare. Many organisms may have thresholds of response rather than a graded dose response (Fig. 4.1) and when these thresholds are exceeded an acute response occurs. 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. In spite of this low probability, acute effects may still be biologically significant when they occur in species, such as marine mammals, that have a relatively low population resilience.
Measuring stress

Behavioral responses to 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) axis 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” may not be indicative of stress because different individuals have widely varying baseline levels of these stress indicators.

Stress, measured in terms of similar hormonal indicators, is less well understood in non-mammals, such as fish and invertebrates. But the concept of stress involving incapacity to adapt or acclimate to immediate environmental conditions is well understood. Nevertheless, 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 samples 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 non-blood 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 non-blood matrices 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 as 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.

Focal animal studies

Since different animal taxa may show fundamentally different responses to sound, the IQOE should focus upon 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 very difficult for other species (e.g., fish,
small odontocetes). Some species may have a lifestyle allowing for very 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 favorable patterns of disturbance (long periods of silence, followed by long periods of activity).

The following is a representative list of potential study species:

- 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

Key studies

The types of comparisons that can be made include:

a) Comparison across species/populations
b) Comparison across habitats/locations/time
c) Comparison before/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:

1. Comparing noisy and quiet environments

Comparing animal behavior, abundance, and productivity between noisy and quiet environments is fraught with 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. However, if chosen carefully it may be possible to examine the responses of animals in different circumstances. 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 between the contrasting acoustic habitats. Specifically, for example, comparisons will be made between the behavior of the same killer whales in fjord habitats with or without boat sound and there will be comparisons between the key faunal attributes of fjords and tropical reefs where there are contrasting influences of anthropogenic sound.

2. Marine pile driving

Offshore developments involving wind farms will result in pile driving on an unprecedented scale within some coastal regions. The impacts 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 of marine species. We propose that these research efforts would benefit from being included within the IQOE.
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. The IQOE will continue to undertake 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 ship sound. Since ship sound is probably one of the most pervasive sources of anthropogenic sound, this will attract most attention. The approaches used will capitalize upon the highly constrained nature of shipping lanes involving pinch points at which ship sound is likely to be greatest. Many of these are easily defined, but circumstances will exist where habitat is shadowed from the acoustic effects of the predictable ship tracks. Some of these shadow regions will be identified as outputs from the soundscape modeling described under Theme 1.

5. 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. 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.

4.4 Research Approach

Strategic approaches to experiments

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

Although large-scale manipulations (up to ocean basin scale) will be important, such as moving shipping lanes from north to south of the Aleutian Islands, there will be an important trade-off between the spatial and temporal scales at which experiments take place and the feasibility of those experiments (Fig. 4.4). Opportunities where the sound exposure can be changed over a 5-10 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.

In ideal circumstances the most appropriate protocol will be to move sound sources to create contrasting (increase and decrease) conditions, and a key element to make this work will be to have enough advance notice (up to 5 years) to establish baseline observations before
changes that are undertaken 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 likelihood will be that the effects will be to
shift from a noisy to a quiet environment.

### Figure 4.4. 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 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 they will combine to deliver some of the benefits that would emerge if we were able to carry out experiments lying to the right of the diagram (from Boyd et al., 2011).

The long-term nature of experimental studies is 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 co-variates.

Experiments should not make the assumption that a directional change in sound will produce proportional change in the response; non-linear responses should be expected and sampling designed to capture such responses.

<table>
<thead>
<tr>
<th>RELATIVELY EASY</th>
<th>POSSIBLE</th>
<th>MODERATELY DIFFICULT</th>
<th>VERY DIFFICULT</th>
<th>NEARLY IMPOSSIBLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACTIVITY</td>
<td>No shut down (observation/monitoring)</td>
<td>Shut down selected anthropogenic sources</td>
<td>Shut down all anthropogenic sources</td>
<td></td>
</tr>
<tr>
<td>SPACE</td>
<td>Regional e.g. new MPAs</td>
<td>Single ocean basin e.g. Arctic long-term changes</td>
<td>Global scale, e.g. comparing basins with high and low ambient sound</td>
<td></td>
</tr>
<tr>
<td>TIME</td>
<td>&lt;24 hours to decades</td>
<td>&lt;24 hours to weeks</td>
<td>&lt;24 hours to days</td>
<td></td>
</tr>
</tbody>
</table>

**Comment [EU11]:** This figure was developed at the first IQOE exploratory meeting to put into context the feasibility of different levels of quieting. Should any changes be made to the figure?
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 2.4 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 3 sub-sites, one in which the exposure is increased, one in which it is decreased, and a third in which the level remains relatively unchanged (Fig. 4.5). Within each site, a targeted set of observations would be made and models 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.

Alternative, and simpler, approaches to this experimental design would be to compare loud versus quiet areas or to measure effects over time in relation to changes in the levels of sound in small localized areas.

Figure 4.5 Schematic showing the experimental design involving three locations.

Comment [EU12]: From George: “Noise” should be “sound”.
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 upon the location, species, and general situation chosen for an experiment. The general assumption underlying the design 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 animals use background sound and may have become acclimated to higher sound levels or even have 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. We raised the possibility above that changes in sound could have non-linear consequences for community structure because even small changes in competitive interactions could have large effects upon the dynamics in marine ecosystems. The same applies to predator-prey interactions.

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 in order to establish the a priori predictions of the effects of the experiment. 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 experiment.

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 focus taxa as those with sensitivity to low-frequency sound.

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

a. High sensitivity of the species to sound;

b. Resident individuals should be preferred over migratory species/individuals;

c. There should ideally be a high level of background knowledge of the species and even individuals if long-lived species are involved. (some whales are known by marking patterns and have been monitored over years);

d. The species is important in the ecosystem, and/or is commercially important, or it has some specific significance to the stakeholder community; and

e. 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.

Given these constraints, there are relatively few species that will fit all of these criteria. In particular, pinnipeds (Figure 4.6), 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 4.6  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 easy to monitor. 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 upon the species being selected for study 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

- 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 and if this did not entail additional cost. In some cases, industry decides on its own to change shipping routes for economic or regulatory reasons.
- 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 could be modeled based upon information from the sound field (Theme 1).

2. Response variables
For each dose, the experiment will have defined response variables. Responses will be measured at different levels of the PCAD model (Figure 2.4), 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/species that leave the area and others that re-colonize can also be measured in terms of 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 (biological and acoustic), turbidity, and ice cover.

4.5 Summary
This theme aims to be the main driver for developing a deeper understanding of the connection between soundscapes and animal responses to the soundscapes. It is, therefore, important that considerable effort is committed to the task set out here.

When complete, these tasks should deliver representative dose-response functions to 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 upon populations. Nevertheless, this will represent a major step forward and, when combined with the outcomes of Theme 1 on ocean soundscapes, will form the basis for making broad predictions about the potential effects of future changes in anthropogenic sound in the ocean.
5

Theme 3: Observing sound in the ocean

5.1 Introduction

Sound in the ocean is challenging to both detect and visualize. This problem is one that requires measurements in five dimensions: three spatial dimensions, plus time and acoustic frequency. The process of measuring ocean soundscapes (see Theme 1) is concerned with characterizing these five dimensions to form a coherent picture. In this theme, 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 towards being able to measure the effects of sound on organisms (Boyd et al. 2008).

Only limited data are currently 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 scientific echo sounders, can provide information on aspects of the ocean environment important to marine life, 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 increasingly technological capability, but also by recognition of the need for new data about the ocean, that sometimes need to be delivered in real time, such as in the case of 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), AUVs (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 frequencies that may be of greatest interest in terms of observing seismic events or other physical changes, such as sea ice breakup, but has less importance in terms of the frequencies that are important to most marine organisms.

5.2 Acoustic observation networks

Dushaw et al. (2009) presented a vision for a Global Ocean Acoustic Observing Network. Wherever possible, acoustic observations need to be included in ocean observing systems designed for other observations. This approach will both contribute 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 the purpose of recording sound in the ocean and many of these are listed in Appendix 1. 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 the process of identifying and cataloging existing and planned acoustical observation systems (see Appendix 1). These systems have been described and tabulated according to several important criteria. The aims of this effort were to show what systems are presently 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 assimilation of acoustical measurements, 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 terms of quality, calibrations, formats, and management in order to enable the comparison of results among international collaborators.

5.3 Acoustics and Global and Regional Ocean Observing Systems

The IQOE cannot unilaterally deploy ocean observing systems because of the resources, experience, and effort required for establishing and operating global and regional ocean observing systems (OOSs). These ocean observing elements include a range of observing technologies, from satellite observations of a variety of oceanic variables to standard NOAA weather buoys to acoustic rain gauges deployed on Argo floats. As noted previously, the ocean is largely transparent to sound, hence oceanographic, biological, engineering, and signal-processing acoustic techniques are primary tools for ocean observation (Dushaw et al., 2009) and represent essential components of the Ocean Observing Systems.

As the IQOE evolves, it will be important to maintain an inventory of OOS capabilities to assess how they can assist the science, and to identify important information that is still missing. 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 IQOE monitoring and experimental efforts is preferred over solely acoustic measurements. However, the type and nature of these ancillary data streams is dependent on the specific question and the environment in which measurements are being made. Indeed, information or data that are missing from existing systems, but are essential for addressing IQOE science questions, will require deployment of additional instrumentation. Some of these deployments will probably transition into operational components of the OOS.
Experience and technologies to promoted 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 the acoustical data streams within the OOS, where appropriate.

The Ocean Observing Systems include within their mandate educational and public outreach efforts. These efforts would naturally extend to any acoustical activities related to the Ocean Observing System (see Theme 4).

5.4 Integration within existing systems

Most or all of the envisioned IQOE monitoring and experimental efforts should leverage data from existing capabilities and/or should 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 continuously updated survey of the known systems (included in Appendix ___ and online at http://aquaticacousticarchive.com/). 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 (Figure 5.1).

Figure 5.1. The locations of existing hydrophone stations of the Comprehensive Test Ban Treaty Organization (CTBTO) (magenta circles) and the regional Australian hydrophone facilities (black triangles) with ocean bathymetry derived from the Smith-Sandwell atlas (ref?). 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. (2009).

These systems were categorized 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 (non-acoustic) data;
- relative accessibility of data from each system;
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- potential integration with other systems;
- sponsoring entity;
- general societal benefit or product of each system; and
- installation duration/life expectancy.

The derivation of the system matrix in Appendix 1 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.

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**Figure 5.2** Sound amplitude in relation to frequency through time recorded at one of the CTBTO sites in Western Australia (see Fig. 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.

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5.5 New systems designed for IQOE

It should be possible to use existing acoustic technologies within existing and planned ocean observation systems. However, it appears unlikely that sufficient monitoring systems with 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 utilize and improve upon 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 directly apply and enhance the information available from existing systems and sensors has been identified in 5 topic areas:

1. **Particle motion/vector sensors**—Research has shown that a majority of fish species are more sensitive to the particle motion component of sound compared 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. **New portable system designed for IQOE (single hydrophone)**— In areas where OOS networks do not have regional nodes or coverage, it will be necessary to develop small, inexpensive, portable systems designed to provide required acoustic, and where necessary, other measurements. These portable systems would provide information relating to the survey of global ocean soundscapes and short-term experiments. Such portable and inexpensive devices will encourage wider international participation in the IQOE.

3. **Modular hydrophones to assemble H/V line arrays**—The ability to quickly and efficiently assemble modular arrays 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 the bottleneck for the transfer of high-volume acoustic data. Developments in this area on either the recording hardware, processing, or data transfer sides would be beneficial to the IQOE effort.

5. **Acoustic backscatter sensors and echosounders**—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 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.

### 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 in the future for observation systems that assess compliance with limits on the additional sound in the ocean from anthropogenic sources. 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 anthropogenic sound production.

There are two approaches to building on this opportunity that could be adopted by the IQOE. 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, their associated monitoring systems could be sources of future datasets and the IQOE has an opportunity to influence the design and placement of such systems.

#### 5.6.1 A survey of historical data to establish the nature of soundscapes of the past

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 the purposes of regulatory compliance,
expansion, research, and targeted surveillance. Some of these data are proprietary or have
national security classifications; whereas other datasets are openly available. At an early
stage, the IQOE will undertake a comprehensive survey of historical data. This could
be accomplished by establishing a database on the IQOE Web site that hosts the working
document and allows for the continual contribution and updating from individual inputs.

Historical data may not be in the format agreed upon by the IQOE, but targeted datasets
could be re-processed for contribution to the IQOE. The information resulting from the
historical data survey and resulting data acquisition would provide information to the IQOE
for providing historical soundscapes in areas of interest for comparison to the present and
for validating contemporary acoustic models.

5.6.2 Sources of future data for 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
Marine Strategy Framework Directive (see Tasker et al., 2010) specifies that all EU member
states monitor their marine environment in order 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, on-going collection of these data to
an IQOE data assembly center.

Since these kinds of data will be formatted primarily to meet the needs of the regulatory
agencies, it will be critical for the IQOE to coordinate with regulatory agencies as early as
possible in order 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 these
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 occurs early in the IQOE). We propose that a standing committee on data
management should emerge from this workshop. Although this example is specific to
Europe, the IQOE should investigate whether similar opportunities or initiatives exist in other
regions of the world and ensure that there is 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 involved in oil and gas exploration and production,
wind-farm deployment and operation, bridge and tunnel construction, offshore mining, etc.,
in relation to 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 unutilized 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.
A specific recommendation is to convene a technology workshop to define standards that will lead to a proposal for the global soundscape project. This workshop would include representatives from the major observing systems, but would be necessarily preceded by specification by IQOE acousticians regarding experimental design. These specifications would 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

There are two parts to this issue, to (1) enable agreement among the acousticians on the standards for data and metadata, and (2) coordinate the acoustical data with OOS or the IQOE DMAC. Appointing a DMAC before the IQOE experimental plan is sorted out is not likely to be helpful.

5.8 Biological Observing Systems

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

Biological observations collected for the purposes of the IQOE may demonstrate their long-term importance and consequently transition to observational status and become elements of ocean observing systems. Combining biological observation with observations of sound will have two specific advantages. First, it 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 the pelagic context) 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. 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 (Figure 4.3).

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 physically 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 inter-related 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 that are presently being 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 2.4), but other modeling approaches will also be used.

Models used within the IQOE will ultimately allow point measurements made locally, regionally, and globally to be used to gain an understanding of how soundscapes change over space and time. In order to develop the most appropriate models, more accurate characterization/measurement of sound sources (biological and anthropogenic) is needed. The utilization of available historical data (e.g., decades of SOSUS/Navy data, 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 fine-scale details derived from new data and oceanographic modeling. See Theme 1 for further discussion of modeling and model validation.

5.10 Recommendations

Monitoring/Experiments for IQOE

Four specific, though not mutually exclusive, types of monitoring and/or experimental efforts are recommended:

1) “Year of Ocean Sound” or “Ocean Soundscape Monitoring Week/Year”

This 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 would occur within a short period of time, but would most logically represent just the beginning of such coordinated observations and modeling. The intention is that this approach would hopefully produce a global map of soundscapes, and that these point measurements would inform subsequent models (see Theme 1). To establish a baseline of the soundscapes of the world’s ocean basins, international coordination would be required to obtain comparable data in different locations. This is envisioned as including two years of organizing, a third year of data collection, and a final year for data analysis and integration. See Theme 4 for further development of this concept.

2) Long-term measurements of chronic sound

A high-priority effort for IQOE should be the initiation of long-term monitoring of sound, particularly at low frequencies, over large/basin scales. The intent would be to focus in a sustained way on characterizing variability in overall sound, anthropogenic contributions, and biological use of areas and possible impacts of anthropogenic sound. Low frequencies would 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.

3) Regional "experiments" or monitoring efforts

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

This could include opportunistic studies (see Theme 2), and could focus on areas of planned
changes in shipping regulations, the no-boat zone in San Juan Islands (before/during/afte),
changes in shipping lanes around the California Channel Islands, designation of Particularly
Sensitive Areas (PSA) (subcommittee within IMO) involving re-routing of ships, and the
presence of transient industrial noise, such as pile driving for the construction of wind farms.
The re-routing of shipping from Unimak Pass to south of the Aleutian Islands to Japan is a
further opportunity. Other opportunities could be available in relation to new gas platforms
installed off Russia, in the Barents Sea involved with new leases, and to changes in
maritime traffic in the Canary Islands area due to logistic and overload issues at other large
container-ship harbors in the Mediterranean Sea and Suez Canal area.

An important action for the IQOE will be to 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.

One typical purely logistical example is that 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. It is
anticipated that this project will have an impact on the traffic during its implementation, some
of which would have to be redirected temporarily along the west coast of Africa. The Las
Palmas harbor in the Canary Islands has the capacity to handle large container ship 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://www.palmasport.es/00000/paginas/asp/noticias_ficha_user.asp?Id_noticia=19292
&codigo_N1=47&codigo_N2=&codigo_N3=).

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. The expected climate changes suggest there is a unique opportunity to
observe the effects of introducing higher levels of anthropogenic noise into this region. 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 ice cover.

Numerous researchers have deployed and will continue to deploy autonomous and cabled
acoustical recording and monitoring systems in the Arctic, and it would be highly
advantageous to incorporate these capabilities into the IQOE. Such systems include
nascent implementation of an observing system for the Arctic (Figure 5.4), for which
Acoustical applications were highlighted during the OceanObs’09 conference (Dushaw et al. 2009). Acoustical applications provide a unique approach to sense or operate under sea ice.

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 likely 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.

Interpreting the results of Arctic studies will be confounded by the influence on the ecology of the natural climatic change in this environment. It might be possible to utilize the conditions in the Antarctic for comparison studies to separate the contribution of climate stressors from sound stressors.

5) Antarctic study comparison

Numerous observational efforts are also underway in the Antarctic using autonomous systems, and the IQOE should coordinate with these efforts as well. 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. An envisioned basin-wide AURORA mooring grid in the Arctic Ocean (left panel) and the existing moored observatory in Fram Strait (right panels). In addition to moored instrumentation, an array of drifting Acoustic Ice Tethered Platforms (AITP) with acoustic modems for communications will be deployed in the Arctic Ocean, while in Fram Strait profiling gliders, capable of under-ice acoustic navigation, will be employed. In the right lower panel, positions of moorings are overlaid on the temperature distribution in Fram Strait, an inflow of the warm Atlantic water in the West Spitsbergen Current depicted by red color (XR: [43]). (From Dushaw et al. (2009).)
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 regulation of 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, both 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 if 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) requires that human activities that could harass marine mammals, including harassment 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. In the case of cetaceans exposed to sequences of pulsed sounds, the threshold at which harassment begins, as defined by regulators is 160 dB re 1 \text{μPa} @ 1 \text{m}. For continuous sounds, the threshold is lower: 120 dB re 1 \text{μPa} @ 1 \text{m}. In the case of pinnipeds, the thresholds are 180 dB re 1 \text{μPa} at 1 m and 160 dB re 1\text{μPa} @ 1 \text{m}, respectively (NOAA 2005, 50 CFR 216). These thresholds correspond closely with the dose-response thresholds defined by the U.S. Navy (see Theme 2).

The effectiveness of these types of regulatory approaches and their impacts (potentially needless) on human activities that produce sound in the ocean have been debated extensively. 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) because ships are the most economical means of bulk transport (Round Table of International Shipping Associations 2011). Perhaps more than 90% 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 (Figure 6.1).
Figure 6.1 Changes in the metric ton-miles of different types of cargos moved by shipping from 1970 to 2010. Source: Fearnley's Review.

A continuing increase in shipping traffic is not certain because there is likely to be an upper limit in the growth of ship transportation of goods brought about by (1) periods of slow or stagnant economic growth; (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. Furthermore, the sound produced by ships is unlikely to increase in proportion to either the number of ships or the tonnage of goods moved because of increasingly efficient and quiet ship designs. This may be borne out in part by 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 2.2 (Andrew et al. 2011). An objective of Theme 1, on ocean soundscapes, is to resolve whether there is a relationship between low-frequency omnidirectional ambient sound and shipping. Figure 6.2 shows the radiated sound spectrum of a passing ship.

It is much more difficult to compile evidence of changes in ocean sound from 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 source to organisms and how organisms react, both individually and as populations. However, only partial progress will be made during the IQOE and considerable uncertainties will remain. It is important that the
IQOE has the capacity to maximize its effectiveness within the arenas of policy and regulation to render current approaches to regulating marine sound more effective. 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 concern undertaking specific research that could provide the basis for more informed approaches to regulation, such as that used by NOAA for regulating effects upon marine mammals (NOAA 2005), but some will involve weaving an applied thread through the activities defined in Themes 1, 2 and 3, and ensuring that the knowledge gained is used in future regulatory activity. Consequently, some of the activities specified in this theme refer to those in other themes.

Figure 6.2 The radiated sound spectrum from a passing ship in which the brighter colors show high sound intensity and where the distance is measured in meters from the ship. From Kozaczka et al. (2010).

6.2 Risk frameworks

6.2.1 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 for the foreseeable future, together with declines in the availability of basic raw materials, including energy resources, creates a strong imperative to continue to exploit ocean resources at least as much as in the present day and probably much more in to the future.

Therefore, industrial development will continue even in the face of increasing regulatory constraints. In these circumstances, it is impossible to wait until scientific knowledge catches up to provide appropriate levels of certainty so that industry can move forward with a high degree of certainty that the options chosen for future development will not significantly impact 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 terms of 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 6.3).
Figure 6.3. 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. 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 pre-determined objectives. If those objectives are not met, mitigation is introduced, the mitigated activity is allowed to continue, and once 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.

- 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 for seismic airguns for example, marine vibrator?
- What environmental 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?

b. Dose-response assessment - Quantitative relation between dose (i.e., received sound characteristics) and response (behavioral response, masking, TTS, PTS, injury). Information needs in this category include the following.
Physical and physiological effects

- Does background sound impact masking and, if so, to what extent?
- 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 exploration and production (E&P) sounds? For example, are large whales more susceptible than small whales or fish?
- Can the hearing range of animals be modeled?
- Can hearing damage from sound be modeled?
- What frequencies can be heard by various species of marine life?
- What impact does long-term sound exposure have on hearing ability of marine life? Is there an effective recovery period?
- Could seismic sources cause animals to become frightened, resulting in vertical flight and the “bends”?
- What are the impacts of industrial sounds on fish and turtles?
- What are the impacts of industrial sounds on prey species?
- What is the relationship between equal loudness curves and audiograms?

Behavioral effects

- What aspects of the sound source are responsible for behavioral response: exposure level, peak pressure, frequency content, etc.?
- What behavioral responses occur when animals are exposed to exploration and production (E&P) sound sources?
- How does E&P sound impact animal displacement? Is it species-specific or do other environmental context factors prevail?
- 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 of masking on animal behavior?
- Do animals become sensitized to repeated sound exposure?

Exposure Assessment

- Distribution and abundance of cetacean/fish stocks over long time periods to identify overlap between sources and receivers
- Quantification of industrial activity in the areas under question
- How does industrial activity translate into sound budgets?
- What is the baseline stressor situation (e.g., what other stressors than sound act on the population under question?)

Risk Characterization

- How can we measure biological significance?
- At what level of effect do we need to be able to detect biological significance?
- With respect to biological significance, are all behavioral reactions equal in importance?
- Are there special biological “hotspots” for animal production that should be avoided at times?
- What is the population growth in areas where sound is prevalent?
Can models (population, energetic, etc.) be used to predict changes in vital rates that could cause biological significant impacts to animal populations?

How do we determine Population Consequences of Acoustic Disturbance (PCAD) transfer functions?

How do we use model output in risk assessments?

Cumulative Impacts: Sound in the context of other pressures to gather a more holistic view of baseline situations.

6.3 Routine sound monitoring

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 but, not only is it necessary to examine amplitude as in this case, other characteristics of the sound need to be determined, such as directionality, bandwidth, kurtosis, particle motion or, in the case of pulsed sound, pulse width, height and rise time. The sound radiated from a source (Figure 6.2) can vary with orientation and, in the case of 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 construction of offshore wind farms. Seismic surveys using airguns are very widespread. Other sources of marine sound include—but are not limited to—construction sound, dredging, acoustic communications, supersonic aircraft, ammunition, explosives, and naval training and surveillance sonars. 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 the characteristics of 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 measuring these values, such as developed by ISO on coastal shipping sound (Ainslie 2011; Carey and Evans 2011). A working group is currently being established by ISO to develop standards for a variety of sound sources, including natural, biological, and anthropogenic sounds, and the IQOE will work closely with this group to adopt appropriate standards. The IQOE will promote these standards through the provision of Web tutorials about their application.

In many regions, statutory monitoring of sound levels is being developed 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 comply with limits to the level of human-generated sound in the ocean.

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 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, in order 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 6.4 illustrates a system of sound monitoring on a local scale that has been developed to provide both regulators and ship operators with a solution to a conflict between, in this case, ship strikes on northern right whales. This system uses acoustic detection of the right whales to alert the ships to their presence.

![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).]

### 6.4 Research priorities for regulators and industry

#### 6.4.1 Defining the biological significance of sound for marine organisms

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. In the Introduction to this Science Plan, the Population Consequences of Acoustic Disturbance (PCAD) model developed by the NRC (2005) was described. This approach leads to the definition of significant biological effects of sound as well as the knowledge needed to define the significance of an effect. From an industry and regulatory point of view, while it would be ideal to understand the mechanisms underlying effects, there is a greater need to move quickly to developing precautionary indicators of significant effects. This may mean that simple, but robust, empirical relationships between sound and responses in marine organisms need to be discovered and used. 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 reduce the confidence intervals around the estimated level of effect.

Studies concerning individual impacts can deal with behavioral response, masking, temporary threshold shift (TTS), and auditory or non-auditory injury. Although it has been shown that, in some cases, sound can injure or even kill marine life, population-level consequences are unlikely, as only a very limited proportion of the population are generally 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 the case of ship collisions and northern right whales (Figure 6.4); 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 re-scaled to develop realistic representations of risk to populations.

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

- To make it possible to scale up the problem through the accumulation of effects on individuals to populations, it will be important to better identify the effects of underwater sound on individual marine animals. This could involve investigations of
  - 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;
  - Masking: experimental evidence that an impact occurs, not only forecasts of effects based on modeling.
- Knowing the spatial distribution of sensitive species and how this changes through time as a way of defining critical habitats for industry to avoid.
- 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.
- Providing key information as defined by a risk-based approach to adaptive management of industrial activity when faced with high uncertainty about the effects of sound.

### 6.4.2 Key topics

Information needs with respect to mitigation measures for industry and regulators include the following:

- What is the effectiveness of existing monitoring techniques and tools?
- What can be done to improve current monitoring techniques and tools?
- What additional monitoring tools (short- and long-term) can be developed to assist in marine mammal observation?
- Can International Maritime Organization (IMO) data be used as an analysis tool on a local and regional basis?
- Can Active Acoustic Monitoring become a viable monitoring tool? Will it be acceptable to regulators and stakeholders?
- 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 current and projected trends in activity levels and sounds produced is important.

Shipping sound and its potential impact on marine life is an area of increasing concern, and has received relatively limited study. Shipping sound can mask communication signals of marine mammals and fish, and both taxa have been shown to change behavior in reaction to these sounds. However, there are uncertainties in assessing impacts of shipping sound. Predictions based on theory indicate that communication ranges can be decreased as a result of increased sound levels; however, understanding the ecologically relevant functional communication range is critically important. There are also large differences in potential effects between deep and shallow waters and among the taxonomic groups affected.
Cavitation sound by propellers is a major source of shipping sound, so mitigation attempts should 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, 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 very close to the source. The issue, however, has been addressed in some regulations such as the MSFD (also see OSPAR, 2009). Although marine pile-driving is generally well regulated in many regions and Environmental Impact Assessments (EIA) are often required, cumulative effects of multiple piling activity, or cumulative effects of piling with other stressors (acoustic and non-acoustic) 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.

In examining the effects of seismic airguns on marine life, the 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 characterizing the source characteristics of seismic airgun arrays, among a range of other studies (e.g., behavioral response study of Australian Humpback whales to seismic airgun exposure), there remains a need for further research in the areas of behavioral effects, masking, and efficacy of mitigation measures.

Additional sound sources to be considered include naval sonars, wave- and tide-energy generation, new exploration technology, dredging, echo sounders, active positioning systems, and fish farming, among a range of others (overview provided by the World Ocean Council). Development of new technologies, such as marine vibroseis, that replaces, where possible, existing sources is strongly encouraged.

Research needed 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 if this should include measurements of specific activities or monitoring of ambient sound.
- In the case of ambient sound monitoring, it is necessary to identify the objective in terms 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 sea observatories in the study area.
  - Assessment of the feasibility of using existing observatories for ambient sound monitoring.
Identification of representative sites (e.g., pressure areas or areas of high sensitivity); and the possibility of establishing reference areas where there is very 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) needs 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, defining these frequencies is important.
- An investigation of the costs and benefits of monitoring is needed to ensure that the outcomes lead to a net benefit for society.

### 6.4.3 Modeling the relationship between industrial activities and sound levels

An important first step in modeling the relationship between industrial activity and sound levels is to define the permissible sound budgets for a region and to compile inventories of human-generated sound in a region to establish whether regulatory targets have been met. This is a particular need of the regulators, but industry also requires 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 towards developing sound budgets, but we do not currently have the sophisticated mechanisms in place to optimize human behavior in a way that matches aspirations.

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 can provide an essential tool for marine spatial planning and informed regulation. The need extends from regional areas of heavy traffic to ocean-basin scales. The goal should be to characterize the present ambient sound conditions and how ambient sound is changing, and to explain the sound field in terms of known sources (natural and anthropogenic) and known propagation conditions using appropriate models. The requirements for model development are

- establishing a program of long-term sound measurements (see Theme 3),
- cataloguing sound sources (see 6.2),
- integrating these into propagation models (see 3.3), and
- validating these models with direct observations (see 5.1).

Robust validated models can be used to evaluate results of sound-constraining regulation, estimating historical sound levels (changing whale populations, economic activity, ship propulsion efficiency) and estimating sound radiated from potential traffic patterns.
6.5 Finding novel solutions

Finally, the IQOE is concerned with developing novel solutions to the suspected problem of the effects of sound on marine life but, in so doing, this drives innovation that will have spin-offs for the overall efficiency with which society operates. If by simply questioning whether we really need to transport >90% of the world’s goods by sea, decision makers can consider the costs involved, and this can drive the development of fundamental innovations that may transform the efficiency of global transport networks. **It will be an objective of the IQOE to work alongside others by modeling transport systems to identify savings that could reduce the human-generated component of ocean sound and, in so doing, find more efficient solutions overall.** The IQOE will work with the World Ocean Council and others to provide appropriate information to maximize the effectiveness of these models.

6.6 Key recommendation

The IQOE encourages the IMO to further address the issue of shipping sound as one of the main contributors to underwater sound in the sea. The IQOE will work in collaboration with the WOC by developing 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 IQOE to global stakeholders, policymakers, and the public.

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 added 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 prioritize underwater sound in very different ways. Researchers operating within the context of the IQOE have an opportunity to 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.

6.7 Engaging Industry and Other Stakeholders

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. The following potential activities would support these goals.

6.7.1 Program “Launch”

To accomplish IQOE goals within an international framework, it is essential that the program become 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 end products being created by this significant international research effort.

It is recognized that the long-term viability of the IQOE depends 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 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, a common message will be
developed to present a consistent image.

It is recommended that the program be “launched” with a suite of activities that include a
scientific symposium, a public lecture, and evening reception with important international
government officials and dignitaries. To attract the international press, these activities should
be held in a high-profile venue such as the Natural History Museum in London, the
Smithsonian Institution in Washington, DC, the Museum of Oceanography in Monaco, or
perhaps several such venues simultaneously.

6.7.2 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 being carried
out by IQOE scientists. It should provide overviews and links to and from each field project.
The portal should include a password-protected IQOE section for project participants. It
should also allow for regulator and industry access to appropriate resources.

Integrated social media should be considered in developing the site. Also provisions will be
necessary for cataloguing image, audio, and video files.

6.7.3 Interactive On-line Database

An on-line database must be developed to allow for the cataloging, sharing, and archiving of
program data. It should provide data access to industry and regulatory representatives.
Periodic on-line training on how to use the data tools and contribute to the database will be
important.

6.7.4 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.

6.7.5 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.

6.7.6 Partner Resources

It is imperative that the IQOE gain the attention and support of public officials and other
stakeholders worldwide. To help facilitate this, 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 to engage stakeholders in their regions. These resources could include fact sheets, maps highlighting on-going research, reproducible graphics, etc. 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, graphic visualizations, etc.

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 JIP and the recently formed working group on underwater sound within the Central Dredging Agency (CEDA) are very important first steps. In general, important roles will be played by the industry associations such as the International Oil and Gas Producers (OGP) and crucial international bodies such as the IMO to help us fill the knowledge gaps.
Implementation

7.1 Project structure

The IQOE is planned to last 10 years in total. The approximate timeline is presented in Figure 7.1. A major feature will be a focus on the work around an *International Year of Ocean Acoustics* (IYOA). An objective will be to conduct as much activity as possible during this year. This coordination will make it possible to focus intensive research, observations, and modeling worldwide and at large scales simultaneously. The IYOA will be used as a focus of public attention on sound in the ocean. However, considerable research will take place in the years before and after the IYOA.

The decadal time scale is needed because the field is beginning from a very low base of organization and working up to an IYOA that will require considerable planning. Similarly, reporting upon studies carried out will require several years to complete partly because of the potential complexity of the data that will emerge and the time that will be required to analyze it. The community of scientists involved at the IQOE Open Science Meeting was enthusiastic about a decadal project.

**Figure 7.1** The proposed timeline for the IQOE, showing the implementation schedule for the five major elements of the program. Additional arrows could be added to show the timing of specific events; those that are labeled in this diagram are for illustration only. More workshops are scheduled during the planning stage than later in the program, but we expect specific meetings to take place to develop funding proposals and to guide the implementation of practical research. There is a plan to hold a conference around Year 9/10 in order to report the results.
7.2 Operating approach

The IQOE will be structured to be a coordinating mechanism for all researchers with an interest in underwater sound and its effects on marine organisms. Research will be funded through traditional national and regional sources. However, the IQOE will not be a simple badging exercise. Any research that will be part of the IQOE will need to be approved by an IQOE Steering Committee (see 7.4). The Steering Committee will apply standards associated with the objective, 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 policy-makers, industry and the public.

7.3 Governance

The IQOE derives its authority from its organizational co-sponsors, 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 in association with conducting regional experiments. As an example, the activities in the United Kingdom of the Underwater Sound Forum, which meets under the auspices of the UK Marine Science Coordinating Committee\(^5\), has the capacity to link directly to the IQOE as a way of building its capacity to develop the evidence base for policies concerning marine sound.

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\(^5\) The MSCC is an inter-departmental committee of the UK government that considers the organisation of marine science because marine issues cut across many different government interests.
of this Steering Committee will report annually to SCOR and POGO about all aspects of the IQOE, including progress in implementing the Science Plan and with outreach and stakeholder engagement. The Steering Committee may have joint chairs, particularly representing biological and acoustical expertise. The Steering Committee will be formed of its chairman, the chairs of the permanent working groups, and as many as 10 additional members. The current plan is to have two standing working groups:

(1) The Working Group on Data Management and Communication will have responsibility for defining the standards of data collection and managing the various systems used by IQOE for communication, including the Web site and associated data portal.

(2) The Science Working Group will have responsibility for determining whether projects proposed by the research community should be included within the IQOE.

Other standing working groups may be set up as the project develops to handle specific tasks.

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.

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.

### 7.4 Project management

Following review and approval of the Science Plan by the sponsors, the Steering Committee (SC) will be selected by project sponsors. With the assistance of the IQOE IPO, the SC will:

- 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 inter-calibration 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 7.5); and
- Report annually to SCOR, POGO and any subsequent sponsors, on the state of planning and accomplishments of IQOE.

SCOR will provide the primary administrative support for the IQOE, at least initially. The project will require at least one staff person whose time is devoted to helping implement and represent IQOE. Duties that will need to be handled by the IQOE IPO include:

- Helping the SC with logistics for meetings and publications
- Representing the project at various meetings
- Fund raising for project activities, working with the SC and sponsors
- Communications and outreach, including Web site, newsletter, etc.
- Management of metadata

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

7.5 Communication
The IQOE 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. The strategy will lead to the provision of literature and other materials that will allow those associated with the IQOE to provide a consistent and clear message. Figure 7.3 illustrates this kind of approach when explaining the derivation of the name of the program. Within 4 words, it is possible to transmit in very simple terms who will be involved, what the program is about, where it will take place (including the frame of reference) and how the program will be conducted.

![Figure 7.3 A diagrammatic representation of how the program name conveys a complex message in simple terms.](image)

7.6 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 specifically 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 6 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 co-fund a program that provides an opportunity for students, technicians, post-doctoral 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, with the major difference being that the terms of SCOR Visiting Scholars is shorter (2-8 weeks) and SCOR does not require the host and Scholar to be pre-matched (see http://www.scor-int.org/SCOR_Visiting_Scholars.pdf).

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 the possibility for the public to record sounds of marine organisms (e.g., through an iPhone application) and to download these 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.

As an example of what should be possible on a larger scale, 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.

There are many other examples of sound from marine organisms available through the Aquatic Acoustic Archive (http://aquaticacousticarchive.com/) and DOSITS (http://www.dosits.org/).

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 of the nature of the specialist technologies, including their complexity, cost, and accessibility. However, the means now exist to make acoustic recording and data logging devices that can be readily used by other researchers without recourse to specialized technical knowledge.

7.7 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 through inviting individuals involved in them to serve on the SSC or other IQOE groups, through workshops of the project, and through regular communication. Some particularly important relationships will include:

- Observing Systems—This report catalogs ocean observing systems that the community believes could be important for implementation of IQOE (see Appendix 1). These include the Global Ocean Observing System (GOOS)—which is a global consortium of specific observing systems—as well as specific systems that may or
may not consider themselves to be part of GOOS, but which either currently include hydrophones or to which hydrophones could be added.

- **Industry and Regulators**—The major sources of human-generated sound are from industries such as shipping, oil and gas exploration and production, energy production, etc. It will be important through the life of the project to keep contact with the relevant ocean industries to ensure that industry 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 the World Ocean Council, as well as individual industry groups, as appropriate. 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 SSC will provide the primary linkage to the relevant portions of the scientific community, including acousticians, marine biologists, physical oceanographers, and others. The IQOE will endeavor to 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 over time. This is the first international project on sound in the ocean and there are no closely related research projects. However, 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.

### 7.8 Work streams and workshops

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

A preliminary set of work streams defined by the Open Science Meeting included:

- Mapping the global soundscape
- Conservation of soundscapes
- Mini-quiet ocean experiment (e.g. at AUTEC)
- Quantifying the increase in anthropogenic ocean sound
- Hydrophones on deep-sea communication cables
- Observing ocean sound field from under Antarctic ice shelves
- Changing soundscapes in the Arctic
- Citizen science: hydrophone on an iPhone (iHydrophone)

In practice, most work streams will be developed through the mechanism of focused, organized workshops, some of which will help the IQOE make early progress on some high-profile topics. The IQOE will, therefore, plan early workshops that will help lay a foundation for the project, providing information needed for future research, observations, and modeling, but which will also provide early visibility for the project through high-impact papers. A list of potential meetings and their sequencing is given in Table 7.1

Four examples of emerging proposals follow, to illustrate the development of the implementation process. The IQOE will develop a process for soliciting and reviewing ideas like these, developing those with sufficient appeal to the community of IQOE scientists.

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7.9 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 foundation for science activities. Support for planning and coordination will be sought from the Sloan Foundation, but also from national science agencies and other national sources, industry, and from other foundations and non-governmental organizations. This support will be used for workshops to create more detailed implementation plans related to IQOE activities described in this Science Plan; to support meetings to establish a data management system, observational standards and protocols, and other infrastructure needed to ensure comparability and access to data gathered worldwide; and to maintain a small centralized staff function. The second kind of financial support will be national 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. 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) funding agencies. Support from the Sloan Foundation would be sought particularly to prepare for the intensive International Year of Ocean Acoustics.
Table 7.1 List and sequence of potential meetings and workshops to implement the IQOE Science Plan

1. Meeting with industry representatives regarding their participation in the IQOE. This meeting would be planned in conjunction with the World Ocean Council and could result in an industry advisory group to the IQOE. The goal of this meeting would be to produce one or more memoranda of agreement between IQOE and industry groups.

2. 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, as well as the 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 would be to develop a written agreement between IQOE and potential providers of information about what information they would make available, under what circumstances, and would describe a mechanism for future discussions.

3. Workshop on design of IQOE data collection, management and access. Issues related to standardization of data collection and storage will need to be addresses early in the project. The goal of this workshop would be to agree to standards and procedures that would guide IQOE observations and research to make observations and research conducted in different locations to be comparable.

4. Workshop of status of modeling relevant to IQOE and needs for the project. This workshop would include discussion of information needed for Population Consequences of Acoustic Disturbance (PCAD0 models. The goal of this workshop would be to provide a roadmap for development of the modeling component of the IQOE. The meeting document will be published in a suitable journal.

5. Workshop on Global Ocean Acoustical Observing System. A proposal for such a system was made at OceanObs'09 (Dushaw et al. 2009). The workshop would revisit that plan and would seek commitments from observation systems to install and support hydrophones, as well as to identify areas of the global ocean where new hydrophone systems should be deployed. The workshop would produce a whitepaper than might be published in the peer-reviewed literature.

6. 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 and after noise levels and effects on marine organisms. This workshop would conduct detailed planning for opportunities that have already been identified, as well as look forward to detect approaches to identify future approaches. The goal of this workshop would be to produce detailed plans for IQOE observations and experiments related to known opportunities, as well as a document that would specify how future opportunities would be approached.

7. Workshop to develop a world map of anthropogenic ocean sound (see Example 1 below). This workshop would 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 CO2 concentrations known as Keeling curves. This workshop would produce a paper for a high-profile journal.

8. Workshop to plan Arctic Ocean acoustic survey (see Example 2 below). This workshop would need to involve scientists involved in acoustics of the Arctic Ocean, as well as organizations involved in Arctic Ocean science and observations. This workshop would produce a plan for an Arctic Ocean experiment that would be part of IQOE.
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. 1 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 unimpacted by human-generated sound
- The map will be made publicly available (in print and in GIS data)

Background and context:
Two studies indicate that ambient sound in the ocean has increased significantly over the past 50 years (Andrew et al., 2011; Chapman and Price, 2011) at frequencies below 100 Hz. Sound at such low frequencies travels across ocean basins with little loss of energy. Both studies attributed the increases to distant shipping. 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 collaboratively 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 (in 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 geoaoustics, 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 7.4. 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, that is, the energy map will not exhibit the same range and distribution of ‘colors’.

Figure 7.4 Shipping density map (Halpern et al. 2008)
Example 2

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

Objectives:

- Make recordings of ambient sound conditions 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 and/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. Conduct observations starting after the period of maximum ice extent in March, but before the minimum in Sept. (see Figure 7.5) using a vessel transit of the NE passage back and forth close to the retreating ice edge;
2. Use dipping hydrophone arrays, towed hydrophones, and bottom-mounted and drifting buoys;
3. Data from buoys and dipping stations will be used to quantify ambient sound levels;
4. Conduct targeted acoustic recordings of specific target individual species;
5. Assemble a team of acoustic and biological experts as a project steering group; and
6. The most practical platform to conduct the study is likely to be a yacht.

Figure 7.5 Map of the Arctic Ocean ice extent together with the median ice edge showing the maximum (March) and minimum extent (September) during 2010.
Example 3
Average ocean noise as environmental status indicator

Objectives:
- Monitor globally averaged low-frequency sound ("ocean noise")
- Identify key parameters to which the ocean noise is sensitive
- Detect changes in the key parameters 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 300 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). A two-step approach is proposed, starting with a feasibility study at the Atlantic Undersea Test and Evaluation Center (AUTEC).

Approach:
9. Identify team able to collaboratively monitor and interpret ocean noise
10. Identify and gather key input data for feasibility study (AUTEC)
11. Model sound sources and propagation at AUTEC
12. Measure sound field at AUTEC and relate to key model input parameters
13. Peer review (e.g., through a workshop) before proceeding to ocean scale
14. Identify suitable ocean (suitable basin; suitable monitoring network)
15. Identify and gather key input data for selected ocean basin
16. Model sound sources and propagation in ocean basin (see also "World Map of Anthropogenic Ocean Sound")
17. Identify and fill critical gaps in hydrophone network
18. Measure sound field in ocean basin and relate to key input parameters
19. Assess feasibility for detecting changes in key parameters (e.g., global thermometer)
20. Write and publish results in a high-impact journal (Nature or Science).

AUTEC 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. AUTEC’s Tongue of the Ocean (TOTO) provides a natural quiet and deep basin, an existing monitoring network, and known shipping activity. TOTO is surrounded by shallow water that for a model-scale experiment would represent the continental shelves surrounding a deep ocean. An important aspect of the feasibility study is understanding how the geometry and frequency scale 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, LIDO and MPEL stations, as well as newly installed stations (EU Member States are required to monitor trends in low-frequency underwater noise from 2014). New hydrophone stations might be needed. In order to provide an indication of any trend, the 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 2007). Because propagation conditions also depend on parameters related to climate change (e.g., sea surface temperature), the possibility also exists of monitoring climate change through changes in the ocean noise Figure 7.6).

Figure 7.6 Does ocean noise reflect trends in sea surface temperature?
**Example 4**  
Marsdiep powerboat race: Effect on soundscape and marine life

**Objectives:**
- a. Produce a three-dimensional map of the sound field in the Marsdiep (see Figure 7.7) before, during and after a powerboat race
- b. Assess the impact of the powerboat race on marine life in the Marsdiep
- c. Identify key inputs needed to model ambient noise on a larger scale

**Background and context:**
The Marsdiep is a natural basin between den Helder on the Dutch mainland and the island of Texel. It is also a foraging area for harbor porpoise and harbor seal populations. A unique opportunity to study the effect of changing levels of anthropogenic sound on marine life in the Marsdiep will be available during a powerboat race (“the Event”) scheduled for August 2012, as well as before and after the Event.

**Approach:**
1. Measure sound field before, during, and after the Event
2. Measure sound sources both during Event and separately under controlled conditions
3. Identify suitable sound propagation model and identify key model input parameters
4. Model the sound field before, during, and after the Event
5. Measure distribution of marine life before, during, and after the Event
6. Identify possible cause-effect relationships between animal behavior and the sound field
7. Write and publish report in a peer-reviewed journal.

The noise background to the Event comprises contributions from both natural (wind and biological) and anthropogenic (boat traffic) sources. The total noise during the Event will be the sum of this background (possibly influenced by the Event), the contributions from the powerboats and any supporting activities. The spatial distribution of the sound will be characterized, as well as the source levels of individual boats. Measurements are envisaged also on a single powerboat under controlled conditions with varying speed.

The effect of the Event on harbor porpoises and harbor seals will be studied. We hypothesize that the sound emissions from the powerboats will have an effect on the animals’ behavior and habitat use. The presence and behavior of harbor porpoises will be monitored by means of aerial and land-based visual observations and acoustic click detectors; harbor seals will be tagged with telemetry units and satellite transmitters. Understanding the behavior of the animals will help in managing the impact of similar anthropogenic events in the future.

It is hypothesized that the Marsdiep’s unique shape, with relatively deep water (ca. 50 m) surrounded by shallow water (ca. 10 m) can be used as a scale model of a larger basin, and that these observations will therefore provide valuable insight to future research on larger scale experiments. An important aspect of the study is understanding how the geometry and frequency scale to a larger basin (see "Average ocean noise as environmental status indicator").

**Figure 7.7**  
Bathymetry of the Marsdiep (Dastgheib et al. 2008)
REFERENCES


Grist et al.


9 December 2011 DRAFT


Tyack (2008)

Tyack (2010)


Wenz 1967

Appendix I
Appendix II
Contributors to Science Plan

Editors

These individuals transformed the outputs from the IQOE Open Science Meeting into a Science Plan, based on experience with previous projects: Ian Boyd, George Frisk, David Farmer, 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 co-chairs and two co-rapporteurs. These groups are responsible for the good ideas and much of the text in this Science Plan.

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):
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Theme 4: Frank Thomsen and John Young (chairs) and René Dekeling and Jason Gedamke (rapporteurs)
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