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A watercolor illustration of an offshore oil rig in the upper half, with its reflection in the water below. In the lower half, a narwhal swims towards the left, its long tusk pointing upwards. To the left of the narwhal is a vertical blue pole with a horizontal bar at the top and a circular weight. The background is a mix of light blue and white clouds at the top, transitioning into various shades of blue and green representing the water. The overall style is artistic and painterly.

MONITORING AND MITIGATION OF THE SOUND EFFECTS OF HYDROCARBON EXPLORATION ACTIVITIES ON MARINE MAMMAL POPULATIONS

Koen Bröker

Monitoring and mitigation of the sound effects of hydrocarbon exploration activities on marine mammal populations

Koen Cornelis Arthur Bröker

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to obtain the degree of PhD at the
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 and in accordance with
 the decision by the College of Deans.

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To my Dad, Mum, Jen & Alma

The sea, once it casts its spell, holds one in its net of wonder forever

-Jacques Cousteau-

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Chapter 1

Introduction

Introduction

Offshore Exploration and Production (E&P) activities, such as seismic surveys and drilling activities, generate sound that propagates well in marine environments. These activities can overlap in space and time with marine mammal populations in different stages of their life cycle. Whether exposure to E&P sounds affects marine mammals depends on the sound levels, frequency and duration of these sound sources. Exposure of marine mammals at varying distances from a sound source can result in different effects ranging from auditory injury, i.e. Permanent Threshold Shift (PTS), Temporary Threshold Shift (TTS) (Southall *et al.*, 2007; Finneran, 2016; Southall *et al.*, 2019), to behavioral responses or disturbance (Nowacek *et al.*, 2007; Ellison *et al.*, 2011) and communication masking (Di Iorio & Clark, 2010; Blackwell *et al.*, 2013, 2015; Cerchio *et al.*, 2014, Erbe *et al.*, 2016, Sills *et al.* 2017). If these sound effects are severe, or continue for prolonged periods of time, and are not mitigated sufficiently, they may result in population level consequences (Villegas-Amtmann, 2015, 2017; Costa *et al.*, 2016; NAS, 2017; Pirota *et al.*, 2018; McHuron *et al.*, 2018).

In order to assess effects of E&P activities on marine mammals one can apply the ‘Source, Pathway, Receptor model’ (Cerrato & Goodes, 2011), which includes (i) the acoustic characteristics of the *source* such as source level, frequency spectrum and duty cycle, etc., (ii) the *pathway*, i.e. the way how sound propagates through the water column, and is affected by environmental and physical conditions (iii) *receptor* specifics such as abundance and distribution and associated seasonal variation, species-specific audiograms and TTS thresholds, sensitivity of species to disturbance, etc. As knowledge gaps may exist within these marine sound risk assessment processes, monitoring programs can be conducted to enhance our understanding of these parameters (source, pathway and receptor).

A range of measures can be applied to mitigate the effects of E&P sound on marine mammal populations. These can be categorized in line with the mitigation hierarchy (avoid, minimize, restore, offset) (IFC, 2012), although for effects to marine mammals the first two steps (avoidance and minimization) are the most common ones. Whereas for most E&P activities a standard set of mitigation measures can be applied (e.g. ramp-up procedures, marine mammal observers, exclusion zones and use of fixed shut-down criteria), other, more high-risk projects, warrant additional ones (Nowacek *et al.* 2013; Bröker, 2019). This can be the case when E&P activities occur in important feeding or breeding areas or could impact endangered species of marine mammals. E&P activities off Sakhalin, Far-East Russia, are a good example of hydrocarbon operations in a sensitive area (Johnson *et al.*, 2007; Yazvenko *et al.*, 2007; Broker *et al.* 2015). East Sakhalin is home to an endangered population of gray whales (*Eschrichtius robustus*), who share their summer feeding ground with several oil and gas developers. Because of the sensitive nature of this population, long-term monitoring studies are conducted to study the change in population size and distribution and to ensure operations have no population level impacts.

4D-seismic surveys are conducted around platforms at regular intervals to detect production-related changes in the reservoir. Because of the close distance between the lease areas where seismic activities are conducted and the feeding grounds, stringent mitigation programs are designed and implemented to ensure there is no, or limited, disturbance to gray whale individuals, specifically to cows with their young (Johnson *et al.*, 2007; Yazvenko *et al.*, 2007; Broker *et al.* 2015). In order to determine the efficacy of specific mitigation measures, monitoring programs can be developed and implemented to gain more insights.

Over the past decades a wealth of understanding has been obtained on the effects of sound on marine life, including marine mammals, which has resulted in enhanced regulatory applications and an improved ability to conduct impact assessments (Gordon *et al.*, 2004; Southall *et al.*, 2017, Broker, 2019). Nevertheless, there are still numerous knowledge gaps which are addressed through research and monitoring programs. When conducting E&P activities in new or sensitive areas, monitoring studies are often conducted to obtain more insights into the abundance and distribution of marine mammals and associated seasonal variation, verify the results of acoustic modeling studies through acoustic monitoring, or to ensure the effectiveness of the applied mitigation measures. This thesis builds on the existing knowledge base and addresses several knowledge gaps associated with the effects of E&P sound on marine mammals.

Two key E&P activities are seismic surveys, where loud, high intensity, low-frequency, sound is used to image the subsurface and identify layers of potential hydrocarbons, and drilling activities (Richardson *et al.*, 1995; MacGillivray *et al.*, 2014, Jiménez-Arranz *et al.* (2017). Industry-led R&D programs are underway to develop alternative energy sources to air guns that have reduced impacts to marine mammals. Example are different types of marine seismic vibrators that emit their energy spread out in time, rather than in a single, high-intensity pulse resulting in reduced source levels (Laws *et al.* 2019). If the results of a seismic survey indicate the potential presence of hydrocarbons, exploratory drilling is conducted to gain information on type of rocks and confirm the presence of hydrocarbons. This is then followed by appraisal drilling to determine the extent of the reserves and production rates. If volumes are expected to be sufficiently large to make development profitable, production drilling can be conducted to extract this resource. One key difference in these activities is that the sound that is generated as part of seismic surveys has a purpose, i.e. sound is used to map the subsurface, whereas with drilling it is merely a by-product of operations without a functional purpose.

This thesis is based on several marine mammal and acoustic monitoring and research studies conducted by Shell, or its Joint Ventures, in the period 2010 - 2015. During this time, Shell had an active focus on arctic hydrocarbon exploration, with exploration operations in, amongst others, Greenland and Alaska, and production activities by its joint venture Sakhalin Energy Investment Company Ltd. in Sakhalin, Russia. Because of the overlap with several sensitive marine mammal species in these geographies, extensive research and monitoring studies were

conducted to address key knowledge gaps. This was needed to better assess and mitigate risks to marine mammal population in or near the project area associated with these activities. These efforts included studies on the abundance, distribution and spatial use of marine mammal populations using different types of methodologies such as double-observer aerial surveys, high-resolution digital aerial surveys, vessel- and shore-based photo-identification studies and passive acoustic monitoring. In addition to monitoring of marine mammal presence, acoustic monitoring was conducted to characterize seismic and drilling sound and verify the results of acoustic modeling efforts. Furthermore, an advanced innovative mitigation program was designed and implemented to minimize impacts of a seismic survey near the summer feeding area of western gray whales, which is described in this thesis. These programs addressed several knowledge gaps (outlined below), and contributed to the existing knowledge base enabling more effective management of E&P risks to marine mammal populations.

Purpose, objectives and research questions

The purpose of this thesis is to advance the protection of marine mammals during the implementation of modern E&P activities through the following themes:

- a. Define the state of knowledge and risks
- b. Evaluate the efficacy of mitigation measures
- c. Advance the scope and capacity of monitoring technologies
- d. Implement advanced industry monitoring and mitigation measures to meet specific conditions and challenges
- e. Provide measurement of heretofore unassessed E&P activities

Specific research questions addressed in these studies that contribute to this purpose and objectives are:

- What is the current understanding of (i) noise impacts of hydrocarbon activities on marine mammals, (ii) mitigation of these noise impacts, and (iii) different types of monitoring programs used to gain information for marine sound risk assessments? (*Chapter 2*)
- What are the differences in use of aerial digital surveys compared to human observer surveys in estimating marine mammal population abundance using line aerial line transect surveys? (*Chapter 3*)
- What conclusions can be drawn from a long-term photo-identification study of western North-Pacific gray whales in terms of site fidelity, population structure and spatial use of feeding grounds off Sakhalin, Russia? (*Chapter 4*)

- Is mitigating for disturbance of marine mammals by seismic surveys possible, and what mitigation measures would be required to execute an 4D seismic survey in the direct vicinity of the summer feeding areas of western North Pacific gray whales without causing disturbance? (*Chapter 5*)
- What effect does a seismic survey have on an undisturbed marine soundscape (*Chapter 6*)
- How accurate is pre-survey long-distance (>10 km) acoustic propagation modeling of seismic sources? (*Chapter 6*)
- How can Passive Acoustic Monitoring programs be used to gain more knowledge of year-round marine mammal presence and movement in remote and inaccessible areas, such as the arctic? (*Chapter 7*)
- What are the source levels of exploration drilling and mudline cellar excavation for different mobile offshore drilling units? (*Chapter 8*)

Outline of this thesis

This thesis is based on studies conducted as part of hydrocarbon-related activities in the period 2010-2015. It covers a range of (sub)arctic geographies, ranging from Sakhalin, Russia, to Baffin Bay in Greenland and the Chukchi and Beaufort seas in Alaska, US. The chapters in this thesis can be categorized in several sections: chapter 2 is an introduction to the multi-disciplinary topic of effects of hydrocarbon exploration activities on marine mammals and provides a comprehensive summary of the current knowledge of E&P sound sources, sound propagation and effects to marine mammals as well as available mitigation measures to manage these risks; chapters 3-7 provide results and findings of various marine mammal monitoring and mitigation programs and associated studies; and chapter 8 is a synthesis of the main findings.

Chapters 2 to 5 are the primary chapters to meet dissertation requirements of the Rijksuniversiteit Groningen. Chapters 6 to 8 are secondary contributions and are included because of their relevance to the topic. They provide additional examples of marine mammal and acoustic monitoring programs conducted as part of exploration activities.

This dissertation is reflective of the multi-disciplinary nature of the marine sound topic and provides an overview of some of the monitoring and mitigation programs implemented in the hydrocarbon industry to manage their effects on marine mammals. Whereas at first sight the chapters in this dissertation may seem unrelated, Figure 1 outlines how they all cover part of the total marine sound monitoring and mitigation scope. This figure provides an overview of most of the monitoring and mitigation types. Furthermore it summarizes how each chapter in this dissertation addresses these different monitoring and mitigation types used to manage E&P effects on marine mammal populations.

Figure 1: Overview of how individual chapters (outer gray circle) in this dissertation cover the different aspects of monitoring (source - yellow, pathway - blue, receiver - green) and mitigation (red) technologies and techniques. Monitoring components are based on table 3 in chapter 2.

This thesis contains the following chapters:

In Chapter 2, “An overview of potential impacts of hydrocarbon exploration and production on marine mammals and associated monitoring and mitigation measures” a concise overview is provided of the different types of effects that hydrocarbon exploration and production can have on marine mammals. Additionally, the available mitigation measures that can be applied to avoid and reduce these impacts are described as well as the existing monitoring technologies needed to understand the availability of marine mammals, and actual impacts.

In chapter 3 “A comparison of image and observer based aerial surveys of narwhal” population estimates of the summer population of narwhal in Melville Bay, Greenland were derived separately on the basis of both aerial observer data and photo imagery. These images were acquired at regular intervals and analysed for presence of narwhal. The derived population estimates from both methods were compared with the objective of determining if image-based aerial surveys, as would be obtained when using autonomous unmanned vehicles, were

compatible with aerial observer data.

In Chapter 4 “Site-fidelity and spatial movements of western North Pacific gray whales (*Eschrichtius robustus*) on their summer range off Sakhalin, Russia“, spatial use of summer feeding grounds of Sakhalin, Russia, by Western Gray whales was defined based on a 13-year long photo-identification dataset.

Chapter 5 provides an overview of one of the most extensive and sophisticated monitoring and mitigation programs designed to avoid and minimize the potential impacts of a 4D seismic survey on the population of western gray whales. The monitoring and mitigation plan was based on real-time observations of gray whales from shore-based stations and verification of sound exposure levels using telemetered acoustic recorders. Shut-down criteria for the seismic sources were applied based on behavioural thresholds.

In chapter 6 “Characteristics of seismic survey pulses and the ambient soundscape in Baffin Bay and Melville Bay, West Greenland” the results of an acoustic monitoring program are presented around an extensive seismic program conducted in 2012, which included measurement of ambient sound levels in 2013 and 2014. This study provides insights in short and long-range propagation of seismic pulses, ambient sound levels and quantifies the increase the sound levels due to seismic activity. The results of an acoustic modelling study were verified with measurements taken during this study.

Chapter 7 “Seasonal trends in acoustic detection of marine mammals in Baffin Bay and Melville Bay, Northwest Greenland” reports on a Passive Acoustic Monitoring (PAM) program conducted in Baffin Bay, Greenland, as part of the same 2012 seismic program. This PAM program covered three seasons and the results were used to describe the seasonal occurrence and spatial distribution of marine mammals in Baffin and Melville Bay.

Chapter 8 “Acoustic characterization of exploration drilling in the Chukchi and Beaufort seas” provides the results of an acoustic monitoring study around sound levels associated with exploratory drilling activities and vessel activity.

Finally, in Chapter 9, a synthesis of the main findings and conclusions of this thesis is presented.

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Chapter 2

An overview of potential impacts of hydrocarbon exploration and production on marine mammals and associated monitoring and mitigation measures

Koen C. Bröker

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Abstract

Offshore hydrocarbon exploration and production (E&P) activities can overlap in space and time with marine mammal populations. These activities, especially seismic surveys, can generate loud sound levels that propagate well in the marine environment. Exposure of marine mammals at varying distances from the source of these sounds can result in a range of different impacts, from auditory injury to behavioral responses and masking. The source-pathway-receiver (SPR) model is a framework often used in environmental impact assessments. In this overview, the SPR model is applied to summarize the current understanding of 1) E&P impulsive sound sources such as air gun arrays and continuous sounds originating from drilling (source), 2) the propagation of sound generated by these sources through the ocean's water column (pathway) and, 3) the impacts of these sounds on marine mammals (receiver). Potential unmitigated impacts of E&P activities on marine mammals can be categorized according to their impact severity and spatial scale, ranging from severe impacts occurring at a small spatial scale to lower level impacts occurring at larger scales (typically, but not always, in the following order: permanent auditory threshold shift → temporary auditory threshold shift → behavioral disturbance → masking). Available monitoring techniques, applied to enhance our understanding of marine mammals as related to the potential full range of E&P impacts from individual behavioral responses up to population level consequences, are also described using the SPR model. Additionally, the range of mitigation measures applied in the E&P industry to prevent unacceptable impacts to marine mammals are provided and categorized according to a mitigation hierarchy (avoid > minimize > restore > offset). Finally, a case is made for application of the ALARP (As Low As Reasonably Practical) principle in seismic mitigation guidelines; that is, the applied mitigation measures in specific E&P activities should be proportional with the assessed risk on marine mammal populations, as well as reasonably practicable to achieve.

Keywords: seismic surveys, drilling, impacts, monitoring, mitigation hierarchy, marine mammals, exploration and production

Introduction

Offshore hydrocarbon exploration activities, specifically seismic surveys, are often associated with generation of loud sound levels that propagate well in marine environments. These activities can overlap in space and time with marine mammal populations in different stages of their life cycle, i.e. during migration or at their feeding and breeding grounds. Exposure to both loud continuous or impulsive marine sounds can potentially have several types of impacts on marine mammals. These can be classified into different categories such as mortality, injury to the hearing system (Permanent Threshold Shift, PTS), temporary reduced hearing sensitivity (Temporary Threshold Shift, TTS), behavioural disturbance, and communication masking. When unmitigated, sound levels generated by some sound sources, such as sonar, can have lethal effects on cetaceans (Simmonds & Lopez-Jurado, 1991; D'Amico *et al.*, 2009). Although inferences have been made that seismic surveys can cause mortality, to date there is no conclusive evidence supporting a connection between marine mammal mortality and seismic surveys. Exposure of marine mammals to air guns at close range or for a prolonged period, however, has the potential to result in damage at the cellular level of the hearing system, commonly referred to as 'injury' (PTS), or a shift in hearing sensitivity measured in decibels referred to as TTS, also known as auditory fatigue (Southall *et al.*, 2007; Finneran, 2016; Southall *et al.*, 2019). Additionally, monitoring studies of various species of marine mammal indicate that animals can respond to sound generated by seismic surveys, drilling, or the presence of industry vessels in manners that include head turning to regulate exposure levels, movement away from the sound, or temporary cessation of behaviors such as feeding or swimming (Nowacek *et al.*, 2007; Southall *et al.*, 2007; Ellison *et al.*, 2011). Another example of potential behavioral effects of sound are impacts to communication between conspecifics, as marine sound has been observed to influence number of vocalizations in baleen whales (Di Iorio & Clark, 2010; Blackwell *et al.*, 2013, 2015; Cerchio *et al.*, 2014). Marine sounds generated by the Exploration and Production (E&P) industry also have the theoretical ability to mask vocalizations used for navigation, communication, or prey localization (Southall *et al.* 2007; Sills *et al.* 2017), although masking demonstration is very difficult, in part because animals possess many adaptations to reduce the likelihood of a sound of interest being masked (Erbe *et al.*, 2016).

The 'source-pathway-receiver' model is often used in environmental impact assessments (Cerrato & Goodes, 2011). This overview paper uses this model as a framework to describe sound sources used in the E&P industry (source), how sound generated by these sources propagates through the ocean over various distances (pathway), and, ultimately, how sound can impact marine mammal individuals and populations (receiver).

Whereas some of these impacts are reasonably well understood because they have been the subject of numerous studies and monitoring programs, such as certain hearing studies using air guns (Finneran *et al.*, 2015; Reichmuth *et al.*, 2016; Kastelein *et al.*, 2017; Southall *et al.*, 2019), there are significant knowledge gaps associated with others, e.g. masking (Erbe *et al.*, 2016). For this reason, key knowledge gaps are being filled through various research programs, with funding

provided by national regulatory agencies, the E&P industry, non-governmental organizations, research institutes, or other entities (e.g., Bröker *et al.*, 2018). Studies are conducted both in laboratory settings and in the natural environment. Additionally, during exploration projects, such as seismic surveys, monitoring programs are sometimes implemented to enhance our understanding of marine mammal responses and to determine the efficacy of applied mitigation measures (Malme *et al.*, 1986, 1988; Yazvenko *et al.*, 2007; Bröker *et al.*, 2015; Martin *et al.*, 2017, 2019; Austin *et al.*, 2018). A range of different monitoring techniques and technologies that can be applied during E&P activities are summarized in this overview paper. Monitoring programs often focus on population level effects, such as changes in distribution and abundance (Muir *et al.*, 2016), or on individual level effects, e.g. changes in swimming, breathing, or diving behavior (Gailey *et al.*, 2016). Over the past several years, extensive progress has been made in the quantification of the link between behavioral changes on an individual level and the possible consequences at a population level (Villegas-Amtmann, 2015, 2017; Costa *et al.*, 2016).

Through monitoring programs and behavioral response studies, significant progress has been made toward enhancing our understanding of impacts of seismic sound on marine life, and which mitigation measures can be used for monitoring and mitigation to avoid or reduce these impacts (Nowacek *et al.*, 2013; NMFS, 2016; JNCC, 2017). Avoidance of impacts can be achieved by planning to circumvent spatial and temporal overlap between E&P activities and presence of marine mammal populations, especially during biologically important life stages such as the breeding season. Some examples of mitigation measures to avoid and/or reduce impacts are to use the lowest possible source levels, reduce sound levels generated by E&P vessels and equipment, eliminate unnecessary high frequencies, ramp-up, and use exclusion zones including shut downs (all further described in the section on mitigation).

Concern over the impact of E&P sounds on marine mammals became more predominant in the 80s (Malme *et al.*, 1984, 1986, 1988). Richardson *et al.* (1995) presented a comprehensive overview of the impacts of all types of marine sound on marine mammals. Since then further reviews on sound impacts on marine mammals have been developed (Evans & Nice, 1996; Richardson & Würsig, 1997; Gausland, 2000; Gordon *et al.*, 2004; Nowacek *et al.*, 2007; Weilgart, 2007; Southall *et al.*, 2007, 2019). This paper builds on those earlier reviews and provides a summary of the relevant knowledge gained over the past decade and provides an up-to-date description of (i) key sound sources used in the E&P industry, (ii) propagation of sound in the marine environment, (iii) types of impacts that E&P activities can have on marine mammals, (iv) the different monitoring methods that are implemented to enhance our understanding of E&P impacts, (v) the mitigation measures currently applied in the E&P industry using the mitigation hierarchy, (vi) a brief summary of international guidelines, and (vii) recommendations for future studies. There is a wealth of knowledge on impacts of sonar and other sound sources on marine mammals, and other forms of marine life, but this has not been included as the focus of this paper is solely on E&P activities and their impacts on marine mammals.

Characterization of Sound

Sound is typically parsed into two components, pressure and particle motion (Stewart, 1932; Popper *et al.*, 2004). Sound pressure in water is the variation in hydrostatic pressure caused by the compression and rarefaction of particles as the sound wave propagates. Particle motion is the oscillatory back and forward movement of particles, which then moves the particles adjacent to them. Particle motion can be expressed as displacement (m), velocity (m s^{-1}), or acceleration (m s^{-2}) (Popper *et al.*, 2004; Slabbekoorn *et al.*, 2019). Whereas most fish and invertebrates primarily rely on particle motion to sense sound (Popper *et al.*, 2003), it is of less importance to marine mammals as evolution of the mammalian ear operating in air has led to a greater dependence on pressure for hearing sound (Finneran *et al.*, 2002). As the focus of this overview paper is on marine mammals, particle motion is therefore not further addressed in this summary.

The primary metrics used to characterize sound are (i) *duration* (expressed in seconds), (ii) *frequency* (expressed in Hz), and (iii) *amplitude* frequently measured in pascals (Pa). Several metrics are used to describe different aspects of the amplitude of a sound with common ones being sound pressure level (SPL) expressed in dB re $1\mu\text{Pa}$, and sound exposure level (SEL) expressed in dB re $1\mu\text{Pa}^2$. Other, less common but still relevant, metrics are rise-time, kurtosis, signal to background noise, or sound level above hearing threshold. (Ellison *et al.*, 2011).

The *duration* of a sound is dependent on the type of source and activity generating the sound. A differentiation is made between continuous sound, which has no well-defined start and end, such as sound generated in a busy shipping lane, and impulsive sound, which has a clear start and end, such as the primary seismic pulses that typically lasts several milliseconds and are repeated every 10-15 seconds. It is a relevant parameter in a biological context as it influences sound exposure metrics such as SEL or equivalent continuous sound level (Leq) that are used to determine when injury can occur to the hearing system of marine mammals. Effective duration is treated differently for continuous and pulsed sound; for this reason, sound threshold levels associated with the onset of auditory injury or behavioral responses can be different for the two types of sound with respect to duration.

The *frequency* (ii) of a continuous sound signal is the number of pressure wave cycles per second (expressed in Hz) and is relevant for two reasons. First, propagation of sound through a marine environment is frequency dependent. In deeper waters, lower frequencies propagate farther due to lower attenuation, which is the loss of sound in the water column caused by absorption, scattering, and leakage out of sound channels (Urick, 1983). Second, marine mammals' perception of sound can be classified into different functional hearing groups, the species in each group having optimum hearing in different frequency bands. Cetacean species are broadly divided into low, medium, and high frequency hearing groups for convenience in predicting the likely hearing spectrum of a given species, even if its audiogram has never been tested directly (Southall *et al.*, 2007; NMFS, 2016, 2018). This is considered reasonable, given the inherent evolutionary conservatism we see in auditory anatomy and function, consistent with the importance of hearing to an individual's survival and reproduction (Southall *et al.*,

2007, 2019; NMFS, 2016, 2018). Southall *et al.* (2019) uses a different classification and makes the distinction between low (LF), high (HF), and very high (VHF) frequency species. The generalized hearing frequency ranges for cetaceans put forward by the U.S. National Marine Fisheries Services are 7 Hz – 35 kHz, 150 Hz – 160 kHz, and 275 Hz – 160 kHz for low, medium, and high frequency hearing groups, respectively (NMFS, 2016). Pinnipeds' hearing ranges are distinguished for animals in air and in water, with the estimated auditory bandwidths for the latter set at 60 Hz – 39 kHz for sea lions and fur seals (otariids) and 50 Hz – 86 kHz for true seals (phocids) (NMFS, 2016).

The *amplitude* (iii) is the extent of variation of the sound pressure. The acoustic energy of a sound wave is proportional to the square of its amplitude. The sound pressure level (SPL) of a sound is given by $SPL = 20 \log (P/P_0)$, with P being the pressure amplitude, and P_0 being a reference pressure level. Sound pressure level is expressed as a relative measure, i.e. referenced to a pressure P_0 of 1 micropascal (μPa) in water and 20 μPa in air (Urlick, 1983; Richardson *et al.*, 1995). This difference in reference between the two media is one of the reasons why SPLs in air and in water are not directly comparable. Acoustic levels such as SPL are expressed in decibels (dB), a unit that has been used historically for calculating acoustic quantities. Due to the logarithmic scale, the decibel offers a convenient way of handling large ranges of values, such as can be the case with sound levels (Urlick, 1983). Relevant metrics of sound pressure level are (1) SPL – the average sound pressure level over a defined period, often one second for a continuous sound or 90% of the duration of an air gun pulse based on accumulation of energy from 5% to 95% (Thode *et al.*, 2010; Martin *et al.*, 2017) (2) SPL_{pk} , peak pressure level – the maximum instantaneous sound pressure in absolute value, and (3) SPL_{pk-pk} , or pressure level peak to peak – the difference between the maximum positive and maximum negative instantaneous sound pressure. Another relevant metric, including for cumulative and aggregate sounds from multiple sources, is the SEL, which is a measure of energy in a signal of a certain duration. This is the time integral over the duration of the exposure of the instantaneous pressure squared with the unit dB re: 1 $\mu\text{Pa}^2\text{s}$ in water (Southall *et al.*, 2007; ANSI, 2013; Finneran, 2015). Whereas SEL is usually referred to as the sound energy over 1 s for continuous sound or over a single pulse (i.e., typically <1 s) for air guns or other pulsed sources, the time frame over which cumulative sound exposure level (cSEL) is estimated can range from a few minutes or hours of one activity, such as a single seismic survey transect, to a full 24-h accumulation of all sound energy from multiple activities. Although 24 h is a rather arbitrary choice without clear biological significance, it is used in recently promulgated guidelines (e.g., NMFS, 2016, 2018) as the prescribed period for cSEL estimation in threshold criteria for the onset of auditory injury. A few reasons why the 24-h period lacks biological significance include (i) animals are not stationary and exposure to anthropogenic sound rarely continues for 24 h due to animal movement as well as source movement for non-stationary sources, (ii) possible periods of silence within the 24-h period are not considered, during which recovery of the hearing system occurs, and (iii) due to the logarithmic scale of sound propagation, it is mainly the closest distance between the source and animal that contributes to the total sound exposure level, which usually occurs in much shorter

periods than 24 h (Martin *et al.*, 2019).

Sound levels from a vessel or an industrial activity are commonly reported as *source* levels (SL), typically referenced to 1 m from the source (measurements generally taken at a distance of 10's to 100's of m in the far field; i.e., the area where the sound field appears to emanate from a single point, and estimated at 1 m range through numerical “back propagation”) for consistency and ease of comparison between sources. By contrast, the reporting of *received* levels, which are sound levels at a receiver arbitrarily located, such as a marine mammal (Southall *et al.*, 2007), must specify the range between source and receiver to provide some sense of the potential dispersion or attenuation of sound energy that has occurred over the propagation distance.

Finally, although there is no scientific basis for making a distinction between sound and noise, they are not entirely equivalent concepts. Whereas sound is a quantity that can be objectively quantified, noise is a subjective label that depends on the perception and viewpoint of sound by a receiver.

Source – Pathway – Receiver Model

Source

Several different acoustic sources are used by the E&P industry to image the sea bottom and the subsurface, sometimes up to 10 km deep. Examples are air gun arrays, multi-beam echo sounders, sub-bottom profilers, side scan sonar, sparkers, and boomers, which all target different subsurface depths by using different source levels, frequencies and beam-widths. For example, multibeam echo sounders are used to map the sea bed and use frequencies in the range of ~12–500 kHz, sub-bottom profilers target the first several hundred meters of depth below the seafloor and use frequencies in the range of 2 – 24 kHz, and seismic airgun arrays target much deeper structures (up to 10 km) and mainly use low frequency energy (~<300 Hz) (Richardson *et al.*, 1995; MacGillivray *et al.*, 2014). Whereas these sound sources can be loud, they have a direct purpose; i.e., penetrate the subsurface to measure the earth's (geo-) properties which are used to determine the potential presence of hydrocarbon deposits. Several other offshore E&P activities generate sounds without such a purpose, with examples including shipping (e.g., liquid natural gas [LNG] and oil tankers), dynamic positioning (DP) systems (as used in deep water drill rigs), and drilling. Thus, a key distinction between different E&P sound sources is that some are used as a sensor or communication device and others are a by-product of mechanical/propulsion systems. This has consequences for the potential applied mitigation measures, as avoidance of needed E&P sound sources is typically not possible and a reduction in source levels could be problematic as it could likely result in sub-optimal performance. On the contrary, elimination or a reduction of sound generated by an activity as by-product (i.e., noise) does not affect the effectiveness of that activity. A comprehensive summary of underwater sounds produced by the E&P industry is provided in Jiménez-Arranz *et al.* (2017).

Air guns - Compared to other E&P sound sources, impacts of air gun arrays on marine life have received the most attention due to concerns over the high amplitude and pulsed sound that are generated at regular intervals (10-15 s) (Caldwell & Dragoset, 2000). Seismic surveys are conducted for periods ranging from weeks to several months, depending on the area to be surveyed. An air gun array consists of several air guns, commonly arranged in a rectangular configuration. The planar array is oriented parallel to the sea surface, typically with the guns simultaneously releasing high pressure air (usually around 2,000 psi, equivalent to 13.8 MPa) into the surrounding water (Amundsen & Landrø, 2010). The air pressure and vent size generate an expanding bubble that creates an initial pressure pulse of very short durations (0.004 – 0.005 s) (Caldwell & Dragoset, 2000; Gisinier, 2016). These arrays are typically towed at depths of 3-10 m below the water surface at speeds of around five knots (2.5 m/s). The high-pressurized air coalesces into a bubble, which generates sound by the ensuing expansion and contraction of the oscillating bubble (Johnson, 1994). The arrays are designed so that the different bubble interactions result in a downward directed, high-amplitude, primarily low-frequency sound pulse that can penetrate the subsurface to depths of several kilometers. Sound propagating through the subsurface is reflected and refracted by the different types of rock layers. Stationary receivers at the sea bottom (nodes) or towed at the sea surface (streamers) record the sound returned from the underlying geology, which is then used to build a two-dimensional (2D) or three-dimensional (3D) image of the subsurface geology (Long, 2006; Gisinier, 2016). This technique significantly increases the rate of success when targeting hydrocarbon reservoir drilling activities. Whereas air gun arrays are designed to be directional, i.e., the loudest sound levels are aimed towards the bottom, there is substantial sound energy propagating into the horizontal plane as well (Caldwell & Dragoset, 2000). Sound levels emitted horizontally are about 20 dB lower than those emitted vertically, with intermediate values observed at intermediate angles (Caldwell & Dragoset, 2000). The pattern of radiated sound is also frequency dependent as the pulses from multiple air guns interact and interfere with each other (MacGillivray, 2006).

The sound levels of air gun arrays (i.e., the source level) depend on the air pressure, the number of individual air guns, and the sum of the volume of each individual air gun in the array. With pressure typically being fixed at 2000 psi, the number of individual air guns and the total volume of the array is varied, depending on the depth of the geological strata of interest and the material composition of the geological layers (e.g., basalt and salt layers are acoustically dense and require more energy to penetrate). Air gun arrays typically range in total volume from 500 to 5000 in³, although arrays up to 8000 in³ are occasionally used, and are usually comprised of 12-48 individual guns with air reservoir volumes in the range of 10 – 500 in³ each. Source levels from individual guns range from 200 to 232 dB re 1 μPa @ 1 m for small to large individual air guns, respectively (Richardson *et al.*, 1995; Hermanssen *et al.*, 2015; Jimenez-Arranz, 2017). Array source levels range from 235 dB re 1 μPa @ 1 m for a small array (500 in³) to 260 dB re 1 μPa @ 1 m for large arrays (7900 in³). Note that these nominal source levels at 1 m do not exist anywhere in, or near, the physical framework of an array that is a distributed source typically up to 20 meters in length and width, e.g. 16 x 16 m. Instead, these are values derived by back-propagating levels measured in

the far field, i.e. far enough from the source that its field appears to originate from a single point. As mentioned previously, source level specifications of air gun arrays refer to sound levels in the vertical direction, with nominal sound levels in the horizontal plane being approximately 10-20 dB lower (Caldwell & Dragoset, 2000). Most of the generated sound is below 250 Hz, with 90% of the energy between 70 – 140 Hz (Tolstoy *et al.*, 2004; Jimenez-Arranz, 2017). However, pulses do contain some higher frequencies, at least up to 16 kHz, albeit of low energy levels (Madsen *et al.*, 2006; Tyack, 2009; Hermanssen *et al.*, 2015; Martin *et al.*, 2017).

Drilling - Whereas sound used for imaging of the ocean bottom and the subsurface geology has a specific objective, sound generated from drilling is a by-product of the mechanical vibration of the rock and drill bit and is therefore considered noise. Some key differences between air guns and drilling activities in sound levels are (i) lower SPLs than those observed with air guns, (ii) continuous for drilling rather than impulsive for airguns, and (iii) drilling levels contain relatively less low frequency energy (Austin *et al.*, 2018). Due to the continuous nature of drilling activities, the total sound energy animals can be exposed to can exceed regulatory thresholds (expressed in SEL) set to minimize impacts to marine mammals (Southall *et al.*, 2007, 2019; NMFS, 2016, 2018). Drilling activities produce different types of sound: (i) sound generated by the rotating drill bit on the substrate, which is often tonal in nature; (ii) sound of cavitation caused by the dynamic positioning thrusters used to keep the drill rig stationary, which is used in deeper waters where anchoring to the sea bottom is not feasible; (iii) noise generated by support vessels; and (iv) noise from equipment and machinery used on the rig such as pumps, generators, engines, hydraulic winches, cranes, etc., which are transmitted into the water column through the hull or gravity-based structure. Details on measurement of drilling activity sound levels are mostly presented in industry and government reports, impact assessments, and permit applications (e.g., Greene, 1987; BOEM 2015). Peer-reviewed literature on this topic is scarce.

Austin *et al.* (2018) reported on measurements taken during drilling activities of three different moored drill vessels in the Arctic Chukchi and Beaufort seas. These activities included drilling of a mudline cellar in the upper sediment (6-7 m in diameter and 11-12 m depth). Mudline cellars are constructed to house the wellhead and blow-out preventer to mitigate risks associated with potential scouring of the sea bed by ice in shallow waters. Acoustic measurements taken during drilling indicated the presence of several tones, with dominant frequencies and harmonics below 2 kHz, and higher harmonics present to 10 kHz. Power generating equipment, engines, pumps, and rotating equipment resulted in tones below 100 Hz. Broadband drilling source levels for these three vessels ranged from 169 and 175 dB re 1 μ Pa @ 1 m. Sounds generated by mudline cellar excavation were more broadband in nature and had higher source levels, ranging between 192 and 193 dB re 1 μ Pa @ 1 m. A drilling sound source verification program was conducted by MacDonnell (2017) during a drilling program using the drilling vessel *Stena IceMAX* in 2,000 m of water. This vessel was held in position with dynamic positioning (DP) thrusters. Recordings taken at 2 km from the drilling activities indicated that the DP thrusters masked most of the sound generated by drilling itself. Thruster noise energy was dominant in

the 50-1000 Hz band, with average source levels of 187 dB re 1 μPa @ 1 m. Drilling tones were detected at 14 Hz at average sound levels of 164 re 1 Hz $\mu\text{Pa}/\text{Hz}$ @ 1 m.

Source Modeling - Seismic source modeling is often conducted to estimate, before the physical device is deployed or even constructed, the specific output of an air gun array in terms of frequencies, directionality, ghost effect (sound reflection from the sea surface), and source levels. The output of these source models can then be fed into propagation models to determine sound levels and their spectral distribution at any range and direction from the source. Source models consider the configuration of an array in terms of the location, number, and volume of individual air guns, pressure, depth, and interaction between the oscillating bubbles released by individual air guns and estimate array output (source levels and frequencies) in the vertical plane (Laws *et al.*, 1990; Tashmukhambetov *et al.*, 2008; Goertz, *et al.*, 2013). Some models estimate in the horizontal plane as well (MacGillivray 2006). Examples of seismic source models are Gundalf (Laws *et al.*, 1990), Nucleus (Goertz *et al.*, 2013), and JASCO's Airgun Array Source Model (AASM) (MacGillivray, 2006).

Propagation (Pathway)

Propagation Fundamentals - Sound travels in water five times faster than in air and with less loss of energy due to the greater density of water. Acoustic energy therefore propagates better in water than in air (Urick, 1983). Sound propagation in water is influenced by numerous factors, such as the sound's frequency, variability with depth of water density, temperature, and salinity, surface and seafloor roughness, bathymetry, and geo-acoustic properties of the subsurface, etc. (Urick, 1983; Lurton, 2010; Wang *et al.*, 2014). As sound propagates away from a source, it is subject to a diminution in sound level referred to as transmission loss (TL). In deeper water, and at ranges away from the source that are smaller compared to the water depth, sound from a point source spreads spherically with transmission loss approximated by $TL = 20\log_{10}[R]$, where R is the distance to the source in (kilo)meters (Urick, 1983). In shallow water (or in a sound channel), sound propagates like a cylindrical front, with energy loss constrained by the water surface and bottom, with $TL = 10\log_{10}[R]$ (Urick, 1983). This means that under ideal propagation conditions, with every 10-fold increase in distance, sound levels generally reduce by 20 and 10 dB in deep and shallow water, respectively. Under most real-world conditions, the average loss of acoustic energy with distance is about 15 dB, commonly ranging anywhere from 12 to 17.5 dB with every 10-fold increase in distance, depending on specific local conditions and the frequency of the sound (Urick, 1983; Richardson *et al.*, 1995; Medwin & Clay, 1998). Low frequency sounds (10-500 Hz) are absorbed by seawater less than higher frequency sounds (Urick, 1983), and sounds below 100-200 Hz can travel distances of several hundred, even thousands, of kilometers at depths of around 800-1000 m due to the temperature-pressure profile of the water column that confines sound in a low-loss layer, referred to as the "Deep Sound Channel," or SOFAR (Sound Fixing and Ranging) channel, (Urick, 1983; Munk *et al.*, 1994; Medwin & Clay, 1998; Širovića *et al.*, 2007). High and very high frequencies (>100 kHz) attenuate rapidly in marine

environments and propagation is usually limited to a few km (Hildebrand, 2009).

Propagation Modeling - Propagation models are used to predict how sound travels through the marine environment and estimate the level of sound at different distances away from the source. As a tool for assessment of potential impacts, propagation modeling can be applied to determine the radii of different impact zones (injury or behavior) around a sound source, and to estimate potential exposure levels of marine mammal populations in critical areas that may be farther away, e.g., on feeding or breeding grounds (Martin *et al.*, 2017). Several different models are used depending on water depth, frequency of the sound, and distance from the source (Jensen *et al.*, 1994; Lurton, 2010; Wang *et al.*, 2014; Ainslie *et al.*, 2016). The Ocean Acoustics Library (www.oalib.hlsresearch.com) provides various modeling packages of these different types of models as well as other useful resources.

Receiver

Exposure, vocalization, and auditory morphology studies have demonstrated that marine mammals have significant differences in their auditory capabilities (Wartzok & Ketten, 1999; Southall *et al.*, 2007, 2019). Because of these differences, cetacean species are categorized as low, mid, and high frequency hearing species. Mysticetes have their optimal hearing at low frequencies with an estimated auditory bandwidth between 7 Hz and 22 kHz (Erbe, 2002; Southall *et al.*, 2007, 2019; Tubelli *et al.*, 2012, 2018; Cranford & Krysl, 2015; Ketten *et al.*, 2016; NMFS, 2016). Most odontocetes are grouped in the mid-frequency hearing range from 200 Hz – 180 kHz. Odontocetes specialized in high-frequency hearing (such as porpoises, the genera *Kogia* and *Cephalorhynchus* and *Lagenorhynchus cruciger* & *L. australis*) have ranges of 275 Hz – 160 kHz. Due to their amphibious nature, pinnipeds are capable of both in-air and in-water hearing. Phocid pinnipeds (true seals) in water have a generalized hearing range of 50 Hz – 86 kHz. Otariid pinnipeds (sea lions and fur seals) in water have a hearing range of 60 Hz – 39 kHz. These generalized hearing ranges are composites based on audiograms of multiple species in their respective groups, resulting in broader ranges compared to the hearing range of an individual species (NMFS, 2016). Some studies suggest little variation in audiograms between species in the same phylogenetical group (Sills *et al.*, 2015), likely due to its importance in survival and social contexts (and echolocation where appropriate). It is this lack of variation at a phylogenetic level that provides some confidence to extrapolate results from just a few tested species to the much greater number of related but untested species.

When discussing impacts such as injury, TTS, disturbance or masking of a species, it is key to consider these species-specific hearing capabilities (Southall *et al.*, 2007, 2019; Terhune, 2013; Tougaard *et al.*, 2015, 2017; NMFS, 2016, 2018) by means of frequency weighting. Frequency weighting is the correction for the frequency-dependent hearing abilities of different species, which helps us to understand how the animals are likely to perceive and use the sound that the physical description of the sound alone cannot provide. Frequency weighting originates from human audiology where different weighting filters are applied (e.g., A- and C-weighting).

Southall *et al.* (2007) further advanced this concept with marine mammals in the form of M-weighting filters, which have been based on the audiograms obtained for several mid- and high-frequency species of marine mammals (and for in-air and in-water pinnipeds). Erbe *et al.* (2016) provides an overview of the marine mammal species whose audiograms have been recorded, which at the time of reporting, consists of 19 species of odontocetes, 13 species of pinnipeds, 2 species of sirenian, and the polar bear and sea otter. In contrast, no audiograms are available for mysticetes, and any weighting curve filter developed is largely based on results obtained from modeling of the mysticete hearing systems (Tubelli *et al.*, 2012; Yamato *et al.*, 2012; Cranford & Krysl, 2015). When discussing auditory impacts, such as injury, behavior, or masking as a function of sound exposure, it is important to note if unweighted or weighted sound levels are being used. The importance of frequency weighting has been established through TTS studies and is increasingly adopted in regulations and guidelines (NFPS, 2016, 2018; Southall *et al.*, 2019). The relevance of frequency weighting for assessing and predicting behavioral responses and masking is starting to be recognized and requires further research (Tougaard *et al.*, 2015, 2017; Kastelein *et al.*, 2019b). When assessing the number of individuals that may be exposed to anthropogenic sound levels that could cause injury or disturbance, acoustic thresholds are applied resulting in exposure zones around the source. The marine mammal distributions, used to derive the number of exposed - or taken - animals within these zones, are often considered as static, i.e. the distribution is considered independent of the exposure levels. An alternative methodology is the application of ‘animats,’ where marine mammal distribution is assumed to be dynamic and dependent on the received sound levels. In these animat models, individuals’ behavior, such as aversion, dive patterns, swim speeds, etc., is programmed to be dependent on sound levels received by those individuals. Although the behavioral dose-response curves are not always well known, use of this dynamic method can provide a more robust framework for assessing risk compared to the static method (Schecklman *et al.*, 2011; Ellison *et al.*, 2016; Frankel *et al.*, 2016; Zedies *et al.*, 2017).

Impact Hierarchy

The potential impacts of E&P sounds on marine mammal individuals can, in general, be categorized by decreasing severity: mortality, injury, temporary threshold shift, behavioural disturbance, and communication masking. With decreasing received sound levels and impact severity, the concentric regions around a sound source where these impacts occur increase in area (Figure 1). For example, injury to marine mammal hearing systems can only occur at high received sound levels, occurring up to several tens or hundreds of meters from an air gun array, whereas behavioral responses and masking can occur at much lower received sound levels and thus in larger areas (Richardson *et al.*, 1995; Ellison, 2011; Cato *et al.*, 2013; Hermanssen *et al.*, 2015). The zones around a source in which impacts can occur are assumed to be two-dimensional and are typically not circular in shape due to, for example, source directionality, sound propagation conditions, and exposure duration. There are exceptions to the order of

these zones. For example, TTS could occur in zones that are larger compared to zones in which behavioral responses happen. This impact hierarchy describes impacts to individual animals, which is not the same as population level impacts. Behavioral responses occur at larger spatial scales and have a lower severity compared to e.g. injury, but if many individuals are disturbed for a prolonged period of time, the population level effects of disturbance are likely to be of more significance than the auditory injury observed in only a few individuals.

Figure 1: The impact hierarchy outlining the different impacts of E&P activities on marine mammal individuals, with a decrease in severity with increasing range of occurrence. Mortality has been omitted from this figure as no causal link between E&P sources and marine mammal mortality has been detected.

Mortality

Anthropogenic sound can result in mortality of marine mammals, as has been witnessed in mass stranding events of beaked whales caused by use of navy sonar in the 2.6 -14 kHz range (Cox *et al.*, 2006; D'Amico *et al.*, 2009). To date, there has been no evidence for a causal effect of marine mammal mortality as a result of hydrocarbon E&P activities, such as seismic surveys or drilling activities. There have been some mortality events near seismic surveys, but these were not attributed to the seismic activity (e.g., Malakoff, 2002). One other inconclusive incident occurred where approximately 75 melonheaded whales (*Peponocephala electra*) succumbed due to multiple secondary factors (e.g., dehydration, sun exposure, etc.) after entering a shallow tidal estuarine system in Madagascar in 2008 (Southall *et al.*, 2013). This uncommon behavior overlapped with a survey vessel using high-powered 12 kHz multi-beam echo sounding (MBES) equipment. An independent scientific panel of the International Whaling Commission, tasked with reviewing this incident, concluded that the exact cause of this stranding could not be determined, but that MBES could not be excluded as a cause (Southall *et al.*, 2013). One issue with determining a causal link between marine mammal mortality and seismic surveys, or other anthropogenic sources, is that it is very difficult to determine from stranded animals whether exposure to sound was the cause of death. Furthermore, it is challenging to assess whether

stranded animals died from direct physiological or anatomical consequences, or indirectly from the consequences of behavioral responses or impacts on communication or navigation (MacLeod & d'Amico, 2006; d'Amico *et al.*, 2009; Villegas-Amtmann *et al.*, 2015, 2017). Although no direct causal relationship between use of air guns and marine mammal deaths has been identified so far, Heide-Jorgensen *et al.* (2013) expressed a concern about increased risk of ice entrapment by narwhal (*Monodon monoceros*) caused by seismic disturbance.

Permanent and Temporary Threshold Shift

Impacts of loud sound on hearing systems are typically distinguished as PTS or TTS. TTS, also known as auditory fatigue, is a shift in hearing sensitivity measured in decibels (Southall *et al.*, 2007). It typically occurs at the same frequencies of the exposure sound, although this is not always the case (Kastelein *et al.*, 2017). The hearing systems of marine mammals are not different from that of humans in that the level of TTS depends on the level and duration of exposure, and the period over which recovery can occur ranges from minutes to days (Hirsh *et al.*, 1955; Charron & Botte, 1988). TTS is a reversible process and, in general, not considered an injury (Verboom & Kastelein, 2005; Southall *et al.*, 2019). PTS, on the other hand, is non-recoverable and occurs after exposure to very loud and/or prolonged sounds (Southall *et al.*, 2007, 2019; Finneran, 2015). The exposure level at which PTS is expected to occur is therefore often used as a criterion for injury determination (Southall *et al.*, 2007, 2019; NMFS, 2016, 2018). This exposure level is based on applied extrapolation methods to predict 40 dB TTS (Southall *et al.*, 2007, 2019), which is not presumed to be similar to the onset of injury as there are no available empirical data to test this assumption.

Based on inner-ear studies of animals accidentally exposed to loud sound sources, it is known that certain sounds cause damage at the subcellular level resulting in auditory injury (Bohne *et al.*, 1985; 1986; Ketten *et al.*, 1993). It has been shown that the cochlear hair cell and the synapse between the hair cell and the primary affected neurons can be lost after exposure, resulting in PTS (Ryan *et al.*, 2016). Over the past decade, a significant number of controlled studies on the impact of various sound sources on marine mammal hearing have been conducted (Southall *et al.*, 2007, 2019; NMFS, 2016, 2018). This is key research as it shapes evidence-based regulations required to minimize the risk of injury to marine mammals, and results of these studies are used to develop marine mammal exposure criteria (e.g., Southall *et al.*, 2007, 2019; Tougaard *et al.*, 2015; NMFS, 2016, 2018; Finneran, 2016). Studies are typically conducted by means of controlled exposure, using specific continuous or pulsed sources, such as air-guns, sonar or recordings of shipping and pile-driving. TTS studies are conducted to determine at which frequencies and received levels, TTS is observed (Finneran, 2015). From chinchilla, and some other animal, through research studies, the relationship between TTS and PTS is known, and hence what additional sound exposure levels are required above the onset of TTS to obtain PTS (Southall *et al.*, 2007). Methods used for TTS studies are summarized in Finneran *et al.* (2015). Different studies can use a different definition for TTS. Southall *et al.* (2007) defines the TTS onset as the exposure needed to produce 6 dB of TTS, but this criterion varies between studies.

TTS-studies using air guns as a source of sound exposure have been conducted on bottlenose dolphins (*Tursiops truncatus*, Finneran *et al.*, 2015), harbor porpoises (*Phocoena phocoena*, Lucke *et al.*, 2009; Kastelein *et al.*, 2017), spotted, ringed and bearded seals (*Phoca largha*, *Pusa hispida*, *Erignathus barbatus*, respectively, Reichmuth *et al.*, 2016). TTS was not observed in all these studies, which can be attributed to different reasons. For example, seismic pulses primarily contain low frequencies that may have less of an effect on mid- or high-frequency species groups (Southall *et al.*, 2007, 2019; NMFS 2016, 2018). Furthermore, in some studies there are indications of self-mitigation by animals. The animals used in these studies can achieve this by actively moving their head away from the sound, by contracting the stapedial muscle in the middle ear (stapedial reflex), or through controlling brain neuronal processes in ways that are not well understood at present (Yost, 1994; Finneran *et al.*, 2015; Nachtigall *et al.*, 2016, 2018; Kastelein *et al.*, 2017). Also, not all species are equally sensitive and reaching sufficient high exposure levels in a controlled environment (shallow holding tanks) in a manner that is safe for the animals can be challenging (Finneran *et al.*, 2015; Kastelein *et al.*, 2017). Typically, smaller individual air guns, scaled to the tank volume, are therefore used. The results of TTS exposure studies are summarized in Table 1. TTS in a harbor porpoise was identified by Lucke *et al.* (2009), using single air gun exposures, with a TTS onset identified at 4 kHz, but not at 32 and 100 kHz, at unweighted SEL of 162 dB re 1 $\mu\text{Pa}^2\text{s}$, weighted SEL of 144 dB re 1 $\mu\text{Pa}^2\text{s}$ (using NMFS (2016) criteria) and peak SPL of 196 dB re 1 μPa . Kastelein *et al.* (2017) conducted a similar study on harbor porpoises with multiple exposures using two simultaneous firing air guns and found significant TTS levels at 4 kHz at unweighted cSEL of 188 and 191 dB re 1 $\mu\text{Pa}^2\text{s}$ for 10 and 20 shots, respectively, equivalent to weighted cumulative SEL levels of 140 dB re 1 $\mu\text{Pa}^2\text{s}$ for 10 shots and 143 dB re 1 $\mu\text{Pa}^2\text{s}$ for 20 shots (using NMFS (2016) criteria). No TTS was observed at 0.5, 1, 2, and 8 kHz (Kastelein *et al.*, 2017). Finneran (2015) exposed three bottlenose dolphins to 10 seismic pulses at a rate of 10 s between pulses. The maximum unweighted cumulative SEL was 193 to 195 dB re 1 $\mu\text{Pa}^2\text{s}$, weighted cumulative SEL was 174 dB re 1 $\mu\text{Pa}^2\text{s}$ (using Southall *et al.* (2007) weighted curves for mid-frequency species), with maximum peak-peak SPL of 200-212 dB re 1 μPa . Although a small decrease in auditory sensitivity was measured, these exposures did not result in moderate TTS (Finneran, 2015), which was defined in this study as ≥ 10 dB. Reichmuth *et al.* (2016) exposed trained spotted and ringed seals to single seismic pulses and measured underwater hearing thresholds at 100 Hz. Received unweighted sound exposure levels ranged from 165 to 181 dB re 1 $\mu\text{Pa}^2\text{s}$ and peak-to-peak sound pressures from 190 to 207 dB re 1 μPa but did not result in observed TTS. Maximum weighted cumulative SEL levels were 171 dB re 1 $\mu\text{Pa}^2\text{s}$ and 156 dB re 1 $\mu\text{Pa}^2\text{s}$, when applying the Southall *et al.* (2007) and NMFS (2016) criteria, respectively.

Table 1: Summary of TTS exposure studies using air guns as source.

Study	Species	Method	Exposure	TSS onset	TTS frequency
Lucke <i>et al.</i> (2009)	Harbor porpoise (<i>Phocoena phocoena</i>)	AEP	Single pulse, one air gun, 20 in ³ , 2000 psi, 14-150m.	unweighted SEL of 162 dB re 1 μ Pa ² s, weighted SEL of 144 dB re 1 μ Pa ² s (NMFS, 2016), peak SPL of 196 dB re 1 μ Pa	4 kHz, not at 32 and 100kHz
Kastelein <i>et al.</i> (2017)	Harbor porpoise (<i>Phocoena phocoena</i>)	Behaviour	Multiple pulses, 1-2 air guns, 5-10 in ³ , 22-120 psi, 1-2m.	10-20 shots of cSEL188 and 191 dB re 1 lPa ² s, weighted cSEL of 140.3 dB μ Pa ² s (NMFS, 2016)	4 kHz, not at 0.5, 1 and 2 and 8 kHz
Finneran (2015)	Bottlenose dolphin (<i>Tursiops truncatus</i>)	AEP	Single air gun, 10 pulses, 40-150 in ³ , 1000-2000 psi, 3.9-7.9m.	No TTS onset. Max. unweighted cSEL of 193 to 195 dB re 1 μ Pa ² s, weighted cSEL of 174 dB re 1 μ Pa ² s (Southall <i>et al.</i> , 2007), maximum SPLpk-pk of 200-212 dB re 1 μ Pa.	Not applicable
Reichmuth <i>et al.</i> (2016)	Spotted seal (<i>Phoca largha</i>)	Behaviour	Single air gun, single pulse, 10 in ³ , 30-100 psi, 1-1.5m	No TTS onset. Unweighted SPL of 165 - 181 dB re 1 μ Pa ² s, SPLpk-pk of 190 to 207 dB re 1 μ Pa, weighted cSEL of 171 dB re 1 μ Pa ² s (Southall <i>et al.</i> , 2007) and 156 dB re 1 μ Pa ² s (NMFS, 2016)	Not applicable
Reichmuth <i>et al.</i> (2016)	Ringed seals (<i>Pusa hispida</i>)	Behaviour	Single air gun, single pulse, 10 in ³ , 30-100 psi, 1-1.5m	No TTS onset. Unweighted SPL of 165 - 181 dB re 1 μ Pa ² s, SPLpk-pk of 190 to 207 dB re 1 μ Pa, weighted cSEL of 171 dB re 1 μ Pa ² s (Southall <i>et al.</i> , 2007) and 156 dB re 1 μ Pa ² s (NMFS, 2016)	Not applicable

The onset of TTS in healthy marine mammal individuals depends on various physical and biological factors. Relevant physical factors are the received sound pressure and exposure levels by the individuals, the frequency content of the sound, and the interval between pulses in case of pulsed sound as recovery of the hearing system occurs during periods of silence (Kastelein *et al.*, 2019a). Biological factors include species and age of the animals. Due to the limited number of exposure studies it is often not possible to base PTS criteria on a single sound source type, such as air guns. Instead, results from all sources, such as studies using sonar, pile driving, air guns, and others are grouped together (Southall *et al.*, 2007, 2019; Tougaard *et al.*, 2015). According to Gordon *et al.* (2004) there is no direct evidence of damage to the hearing systems of marine mammals caused by seismic surveys. Since then, no new observations seem to contradict this conclusion. Studies on bottlenose dolphins, beluga whales (*Delphinapterus leucas*), harbor porpoises, and false killer whales (*Pseudorca crassidens*) suggest that odontocetes have the ability to self-mitigate impacts of loud sounds on their hearing systems by reducing their hearing sensitivity (Supin *et al.*, 2005, 2010; Nachtigall & Supin, 2008, 2014; Linnenschmidt *et al.*,

2012; Supin & Nachtigall, 2013; Finneran *et al.*, 2015, Nachtigall *et al.*, 2016). To what extent this applies to other marine mammal species is currently unknown.

Behavioral responses, disturbance and stress

Sound-generating E&P activities such as seismic surveys, drilling or pile-driving can result in different types of responses by marine mammals, most of which are considered as disturbance. Responses to anthropogenic marine sound can be grouped into behavioral and physiological responses. Examples of behavioral responses are changes in surfacing, diving, and travel direction, and includes acoustic responses such as changes in vocalization rates (increase, decrease or cessation). Physiological responses include changes in respiration variables, temporary thresholds shifts (TTS) and stress (Nowacek, 2007). Southall *et al.* (2007) categorized behavioral responses into 10 qualitative categories of severity based on observed magnitude of response, ranging from low severity responses (1) such as brief orientation changes, to medium severity responses (4-5) such as moderate or extensive changes in locomotion speed, direction, respiration rates, and dive behavior. High severity responses (9) were defined as outright panic, flight, stampede, or stranding events. A summary of many of the response studies from the scientific literature along with the received sound characteristics (frequency and amplitude) is summarized in Nowacek *et al.* (2007).

Behavioral responses by marine mammals to anthropogenic sound sources are observed over a wide range of distances between the source and the animal, with low-severity responses at maximum distances of up to 70-80 km. (Finley *et al.*, 1990; Erbe & Farmer, 2000). Typically, responses are reversible, i.e. upon cessation of the disturbance, the behavior returns to normal (Gailey *et al.*, 2016, Brandt *et al.*, 2018).

Understanding of behavioral responses to air guns and other sound source originate from field and laboratory studies. In laboratory studies animals are exposed to predetermined sound levels under controlled conditions by using small air guns or play back of noise recordings as a source (Kastelein *et al.*, 2013; Finneran *et al.*, 2015; Reichmuth *et al.*, 2016). Whereas the sound exposure levels in studies with captive animals can be controlled, some disadvantages of these studies include proximity of the receiver to the air gun, limited movement space, inability of the exposed animal(s) to move away from the source, and possible habituation of the animal to the exposure sound. During behavioral response studies (BRS) in the field, animal behavior in open water is concurrently studied while individuals are exposed to air gun pulses (Gailey *et al.*, 2015; Dunlop *et al.*, 2016; Dunlop *et al.*, 2017a, 2017b) (Table 2). Based on the source levels, sound propagation conditions, and distance to the receiver, the received levels are estimated, which can consequently be used to develop dose-response curves (Gailey *et al.*, 2015; Dunlop *et al.*, 2017b). Some challenges with BRS in the field are the inability to control the received exposure level by the receiver, permit restrictions on exposure of animals to loud sound levels out of concern for hearing injury, and to obtain a sufficient sample size to make statistically meaningful conclusions (Dunlop *et al.* 2012; Gailey *et al.*, 2015). To address the fact that marine mammals cannot be observed while diving, archival or telemetered tags can be attached to marine mammals to record

small scale behavioral responses to anthropogenic activities. Tag sensors can measure depth (pressure sensor), 3-D movement (accelerometer, magnetometer), light (photo sensor), position, and sound exposure (hydrophones) (Southall *et al.*, 2012; Miller *et al.*, 2012; 2014; Sivle *et al.*, 2015; Van Beest *et al.* 2017).

Development of behavioral threshold criteria, like the acoustic metrics used for the onset of injury thresholds (peak SPL and cSEL), to minimize behavioral responses to anthropogenic activities has proven to be difficult. This is mainly because there is typically no straightforward correlation between the severity of response(s) and received exposure levels (Southall *et al.*, 2007; Ellison *et al.*, 2011). Recent studies suggest that in addition to acoustic metrics, the severity of behavioral responses also depend on various factors beyond exposure levels, such as (i) the activity state of animals exposed to the sound (e.g., feeding, nursing a calf, migrating, etc.), (ii) the type and novelty of a sound, (iii) the spatial relations between a sound and the animal hearing the sound (e.g., is the sound approaching or moving away) and (iv) age-sex classes (Ellison *et al.*, 2011). Therefore a single number dB threshold as an absolute indication of behavioral disturbance is not reliable, and dose-response curves contain significant variation (Southall *et al.*, 2007; Nowacek *et al.*, 2007; Dunlop *et al.*, 2017b). Learnings from BRS are presented below.

Malme *et al.* (1986, 1988) conducted behavioral response studies that examined responses of migrating and feeding gray whales (*Eschrichtius robustus*) to seismic survey sounds in the northern Bering Sea. It was determined that 50% of the whales stopped feeding at received sound pulse levels of 173 dB re 1 μ Pa (rms). Approximately 10% of the animals interrupted feeding at received pulse levels of 163 dB re 1 μ Pa (rms). From these studies, 163 dB re 1 μ Pa has been applied as a behavioral response mitigation threshold during seismic surveys in the direct vicinity of a feeding ground of gray whales off Sakhalin (Yazvenko *et al.*, 2007; Bröker *et al.*, 2015). Despite the application of this mitigation criterion, behavioral responses and changes in distribution, including changes in swim speed, reorientation rate, distance from shore, blow interval (i.e., respiration rate), and dive time were observed in gray whales during a 3-D seismic survey off Sakhalin in 2001 (Gailey *et al.*, 2007; Johnson *et al.*, 2007; Yazvenko *et al.*, 2007). No changes in behavior were identified during another 3-D seismic survey, however, where the 163 dB re 1 μ Pa mitigation criterion was used again during a seismic survey in the same location off Sakhalin in 2010 (Bröker *et al.*, 2015, Gailey *et al.*, 2016). The behavioral responses that were observed during this 2010 seismic survey were associated with vessel proximity, which suggested some non-sound related disturbance (Bröker *et al.*, 2015, Gailey *et al.*, 2016). As part of this seismic survey, it was hypothesized that gray whale individuals would move closer to shore during the survey, but no significant effects of cumulative sound on distance from shore were observed (Muir *et al.*, 2015b). Cumulative sound from the seismic activity over a three-day period on occupancy and densities suggested avoidance of higher cumulative sound exposure levels associated with a prolonged period of exposure, although the influence of prey availability could have caused these changes as well (Muir *et al.*, 2016). Behavioral response studies of bowhead whales (*Balaena mysticetus*) to seismic surveys have been conducted since the early 1980s (Richardson *et al.*, 1985, 1986; Ljungblad *et al.*, 1988). Robertson *et al.* (2013)

concluded that changes in behavior, such as displacement, change in blow interval, and surface time exhibited by bowhead whales exposed to seismic operations are context-dependent. This is supported by other studies demonstrating that feeding or socializing bowhead whales are less likely to avoid seismic surveys than migrating whales (Richardson *et al.*, 1999; Miller *et al.*, 2005; Koski *et al.*, 2009).

Goold (1996) studied the avoidance behavior of common dolphins (*Delphinus delphis*) to seismic surveys in the Irish Sea. Findings suggested an avoidance reaction by common dolphins to air gun emissions. Observations also suggested tolerance to these sounds outside a 1 km radius of the guns, equivalent to a SPL of 133 dB re 1 μ Pa. Localized avoidance by ringed, spotted, and bearded seals of a full active seismic array (1,320 in³) in the Alaskan Beaufort Sea was also observed by Harris *et al.* (2001), where seals were found to avoid the zone closest to the seismic vessel (<150 m). No avoidance was observed beyond 250 m from the vessel, nor were seals observed to vacate the area of operations. Madsen *et al.* (2002) investigated the behavior of sperm whales (*Physeter macrocephalus*) in reaction to a distant (> 20 km) seismic survey. Estimated maximum SPLs received at the whales were 146 dB re 1 μ Pa (pk-pk) and maximum SEL of 124 dB re 1 μ Pa²s. No observable avoidance or changes in vocalization behavior were observed during the 13 d of exposure. Dunlop *et al.* (2016) applied a 20 in³ single air gun firing at 11-s intervals to expose southward migrating humpback whales (*Megaptera novaeangliae*) on the east coast of Australia. Received SELs ranged from 105-156 dB re 1 μ Pa². Animals responded by decreasing dive time and migration movement speed, but this was also identified during controls using the survey vessel without an active source. It was, therefore, suggested that these behavioral changes were a response to the presence of the source vessel. Dunlop *et al.* (2017a) continued similar exposure studies with a 3130 in³ commercial seismic array. Although no abnormal behavior was observed, changes in the magnitude and rates of typical behaviors, such as movement patterns, dive/respiratory parameters and breaching rates, were detected in response to the full seismic array. These changes were detected in the control group as well (i.e., presence of vessel without active source), leading Dunlop *et al.* (2017a) to conclude these were likely responses to the presence of the ship and the air gun sounds. Additionally, slower migratory speeds were observed during air gun exposures, typically within 4 km of the array at received SEL levels over 135 dB re 1 μ Pa²s. No evidence of significant additional stress was identified during the experimental trials, and behavior of the whales was primarily driven by other whales and need to socialize and migrate (Dunlop *et al.*, 2017a).

Miller *et al.* (2009) used acoustic and movement-detecting tags to investigate response of sperm whales to seismic surveys at distances of 1-13 km. They concluded that sperm whales did not respond to start-up or approach of an air gun array with a change in behavioral state or direction of movement. Although not conclusive, the results suggested there was an indication of changes in foraging behavior. Changes in sperm whale foraging behavior in response to low-frequency active sonar (1-2 kHz) was observed by Isojunno *et al.* (2016), where animals switched to a non-foraging state at exposure levels of 131-165 dB re 1 μ Pa. These changes were not observed during exposure to medium-frequency active sonar (6-7 kHz) at exposure levels of

73–158 dB re 1 μ Pa.

Van Beest *et al.* (2017) equipped 5 harbor porpoises with high resolution location and dive loggers after which they exposed the animals to a 10 in³ air gun at ranges of 420 – 690 m, with received noise level estimates of 135–147 dB re 1 μ Pa²-s. One animal displayed rapid and directed movements away from the source, two animals were observed to make shorter and shallower dives than usual, and two animals did not display changes in behaviour.

Stone & Tasker (2006) reviewed marine mammal observer data from 201 seismic surveys conducted in UK waters. They concluded that responses to seismic surveys were taxonomic group-specific; small odontocetes demonstrated the strongest lateral spatial avoidance, i.e. up to beyond line of sight, with mysticetes and killer whales (*Orcinus orca*) displaying more localized spatial avoidance. Long-finned pilot whales (*Globicephala melas*) only adjusted their orientation and sperm whales showed no statistically significant effects. They also concluded that animal responses to active air guns were greater when large volume air gun arrays were used in seismic surveys, compared to when smaller volumes of air guns were used (Stone & Tasker, 2006).

Similarly, Barkaszi *et al.* (2012) reviewed mitigation observation data collected in the Gulf of Mexico, USA, for the period 2002–2008. A total of 194,273 visual survey hours were analyzed including 3,963 complete sighting records of 28,000 individual animals. There were 32 delays in ramp-ups due to the presence of protected species in the exclusion zone during the 30 min. prior to ramp-up resulting in a total delay of 18.5 h of down time. Furthermore, for 144 cases, whales, mostly sperm whales, were visually detected in the exclusion zone resulting in a shutdown of airguns. Shutdowns took on average 58 min. with a total of 125.74 h of down time attributed to shutdowns. The average shut down frequency for sperm whales was 1 shutdown for every 1,500 h (or roughly 125 d) of daylight survey operations. The average distance of dolphins to airguns increased with increasing power output. At full power, the mean closest approach of dolphins to airgun arrays was 90% further away than during silent status.

Blackwell *et al.* (2013) assessed the effects of air gun sounds on bowhead whale calling behavior during the autumn migration in the Alaskan Beaufort Sea. With the start of seismic surveys, call rates increased as soon as air gun pulses were detectable (80–85 cSEL_{10-min} dB re 1 μ Pa²-s), compared to calling rates without seismic activity. After this initial increase, calling rates leveled off at a received cSEL_{10-min} of ~94 dB re 1 μ Pa²-s and calling rates remained high until cSEL_{10-min} exceeded ~127 dB re 1 μ Pa²-s, where whale calling rates began decreasing. Above ~160 cSEL_{10-min} dB re 1 μ Pa²-s whales were virtually silent (Blackwell *et al.*, 2013).

An increase in vocalization rates in response to exposure to a low-medium power technology (sparker) was observed in blue whales (*Balaenoptera musculus*) (Di Iorio & Clark, 2010). The authors speculated that this could have been a compensatory behavior to the elevated ambient noise from seismic survey operations (Di Iorio & Clark, 2010). Cerchio *et al.* (2014), on the contrary, found in a study on the effects of seismic surveys on humpback whale calling rates that there was a significant reduction in the number of whales singing with increasing received level of seismic survey pulses.

Whereas most of the behavioral studies on E&P sources involve use of air gun array as a

source, Richardson *et al.* (1990) also conducted playback studies of drilling and dredging noise on bowhead whales. Roughly half responded when the received level of noise was about 115 dB re 1 μ Pa on a broadband basis, or about 110 dB in one 1/3-octave band (20–30 dB above ambient). These levels were equivalent to about 3–11 km from a drillship and dredge barge in the Canadian Beaufort Sea. As bowheads were seen within 5 km from drilling and dredging activities, Richardson *et al.* (1990) suggested that disturbed animals may habituate to prolonged noise exposure, or, alternatively, only the less sensitive individuals may occur at closer proximity to drill ships and dredges.

Exposure is known to cause stress and have the potential to cause changes in hormone levels (Gordon *et al.*, 2004). Few studies have been conducted on the impacts of E&P sound sources on stress levels. Thomas *et al.* (1990) tried to quantify stress levels by measuring hormone levels (catecholamines) in captive beluga whales exposed to playback of drilling noise (source level 153 dB re:1 μ Pa @ 1 m) but did not find changes, which could have been attributed to the short exposure periods or adaptations to noisy environments (Gordon *et al.*, 2004).

In summary, behavioral responses depend on a combination of factors such as received levels, habituation, auditory sensitivity, and context, i.e. behavioral state and directionality and distance to source. Most, if not all, observed behavioral changes in field studies in response to exposure to seismic survey and drilling activities are up to moderate severity (response score 4-5 for severity scoring in Southall *et al.*, 2007).

Table 2: Summary of changes in behavior, vocalization, and stress hormones in air guns studies (unless mentioned otherwise).

Study	Species	Exposure	Observed behavioural change
<i>Behavioural changes</i>			
Malme al. al. (1986, 1988)	Gray whales (<i>Eschrichtius robustus</i>)	163 dB re 1 μ Pa (rms) 173 dB re 1 μ Pa (rms)	10% of the whales interrupted feeding 50% of the whales stopped feeding
Goold (1996)	Common dolphins (<i>Delphinus delphis</i>)	133 dB re 1 μ Pa	Tolerance to these sounds outside a 1 km radius of the guns
Harris <i>et al.</i> , (2001)	Ringed (<i>Phoca hispida</i>), spotted (<i>Phoca largha</i>), and bearded seals (<i>Erignathus barbatus</i>)	Presence of seismic survey, no exposure levels provided	Avoid of the zone closest to the seismic vessel (<150m), but no avoidance beyond 250 meters from the vessel, nor were seals observed to vacate the area of operations.
Madsen <i>et al.</i> (2002)	Sperm whales (<i>Physeter macrocephalus</i>)	146 dB re 1 μ Pa (pk-pk); SEL of 124 dB re 1 μ Pa ² s (>20km)	No observable avoidance or changes in vocalization behaviour were observed
Yazvenko <i>et al.</i> (2007)	Gray whales (<i>Eschrichtius robustus</i>)	<163 dB re 1 μ Pa (rms)	Changes in behaviour and distribution (swim speed, reorientation rate, distance from shore, blow interval and dive time)
Miller <i>et al.</i> (2009)	Sperm whales (<i>Physeter macrocephalus</i>)	Seismic surveys @ 1-13km.	No response to start-up or approach of an air gun array with a change in behavioural state or direction of movement. Possible change in foraging behaviour.
Robertson <i>et al.</i> (2013, 2015)	Bowhead (<i>Balaena mysticetus</i>)	Presence of seismic survey, no exposure levels provided	Changes in surfacing, respiration and diving behaviour

Table 2: Conintued

Study	Species	Exposure	Observed behavioural change
Bröker <i>et al.</i> 2015	Gray whales (<i>Eschrichtius robustus</i>)	<163 dB re 1 μ Pa (rms)	No significant changes in behaviour or distribution
Dunlop <i>et al.</i> (2016)	Humpback whales (<i>Megaptera novaeangliae</i>)	105-156 dB re 1 μ Pa ² s	Decreasing dive time and migration movement speed, also identified during controls using the survey vessel without an active source.
Dunlop <i>et al.</i> (2017a)	Humpback whales (<i>Megaptera novaeangliae</i>)	>135 dB re 1 μ Pa ² s @ 4km.	No abnormal behaviour, but changes in the magnitude and rates of movement patters, dive/respiratory parameters and breaching rates. Similar changes were detected in the control group as well. Slower migration speeds.
van Beest <i>et al.</i> 2017	Harbor porpoise (<i>Phocoena phocoena</i>)	135–147 dB re 1 μ Pa ² -s @ 420–690m	Avoidance behaviour, shorter and shallower dives.
Acoustical changes			
Richardson <i>et al.</i> (1990) (drilling recording)	Bowhead (<i>Balaena mysticetus</i>)	115 dB re 1 μ Pa of playback	Vocalisation response by half of animals in the area.
Blackwell <i>et al.</i> (2013)	Bowhead (<i>Balaena mysticetus</i>)	80-85 cSEL _{10-min} dB re 1 μ Pa ² -s ~160 cSEL _{10-min} dB re 1 μ Pa ² -s	Increase in calling rates Animals stopped calling
Physiological changes			
Thomas <i>et al.</i> (1990) (drilling recording)	Beluga (<i>Delphinapterus leucas</i>)	153 dB re:1 μ Pa @ 1m	No changes in stress hormones (catecholamines)

Despite the numerous studies of direct responses of animals to sources of disturbances, it is usually difficult to quantify what effect these responses have on the fitness of the individual and population. Various frameworks have been developed to enhance our understanding of the consequences of behavioral responses of individuals at a population level – often referred to as Population Consequences of Acoustic Disturbance (PCAD) or Population Consequences of Disturbance (PCoD) (Villegas-Amtmann, 2015, 2017; Costa *et al.*, 2016; NAS, 2017; Pirodda *et al.*, 2018; McHuron *et al.*, 2018). In these frameworks, the impact of observed behavioral responses on the health of an individual is first assessed, and consequently how changes in health affect critical life-history traits such as survival or reproduction. This is usually conducted through development of bio-energetics models that quantify the reduction in bio-energy intake as a function of disturbance and assess this reduction against the bio-energetic need for critical life history traits such as reproduction and survival (Costa *et al.*, 2016). Finally, the consequences of changes in life history traits on the development of a population are assessed through population modeling. Although these frameworks are usually complex and under continual development, they have been used to assess the population consequences of disturbance in real-life conditions (Villegas-Amtmann, 2015, 2017; Costa *et al.*, 2016; NAS 2017; Pirodda *et al.*, 2018; McHuron

et al., 2018). The PCAD/PCOD model uses and synthesizes data from (behavioral) monitoring programs, ecological studies on animal movement, bio-energetics, prey availability, and mitigation effectiveness to assess the population level effects of multiple disturbances over time (Costa *et al.*, 2016).

Masking

Auditory masking is the interference of anthropogenic or natural noise with the way in which marine mammals receive acoustic signals for communication, social interaction, foraging, or navigation (Clark *et al.*, 2009; Erbe *et al.*, 2016). Masking can occur when an extraneous sound covers or ‘masks’ a desired sound signal, making the latter more difficult to detect (Nowacek, 2007), and masking is quantified as the number of decibels by which an auditory detection threshold is raised in the presence of an interfering sound/noise (American National Standards Institute, 2013; Erbe *et al.*, 2016). Masking of sounds needed for key life functions may have a long-term impact on the individual fitness of marine mammals. Our understanding of masking-related impacts on individuals, however, is currently still poorly understood.

Masking depends on a variety of factors that are summarized in a comprehensive overview by Erbe *et al.* (2016). Relevant variables influencing masking are the location of the vocalizing animal (sender), the sound level, spectral characteristics, and directionality. The signal propagates through the marine environment with variation in acoustic properties. At the location of the receiver, the natural and/or anthropogenic noise levels determine the level of potential masking. Additionally, characteristics of an animal’s hearing system, such as sensitivity and different types of masking release, are examples of important variables at the receiver end (Erbe *et al.*, 2016). Masking release refers to the process and the amount by which expected masking is decreased by some manipulation of the masking or target sound (Oxenham, 2014). Examples of anti-masking strategies are frequency and amplitude comodulating, i.e. varying the pitch and loudness, by altering the vocalization characteristics in the presence of noise (Scheifele *et al.*, 2005; Holt *et al.*, 2011; Hotchkiss & Parks, 2013; Dunlop *et al.*, 2014; Erbe *et al.*, 2016). Reichmuth (2012) states that current models of auditory masking in marine mammals oversimplify hearing in realistic environments and recommends systematic and progressive studies using psychoacoustic methods, i.e. studies on sound perception, to gain a better understanding of masking effects. Sills *et al.* (2016) conducted a masking study using air gun pulses recorded at one and 30 km away from an active array. Spotted and ringed seals were trained to detect a low frequency tone (100 Hz) within these pulses to evaluate how air gun sounds can interfere with detection of low-frequency sound. A second objective was to determine how standard audiometric data (such as audiograms) can predict the extent of masking. Sills *et al.* (2016, 2017) concluded that critical ratios alone are not sufficient to predict the full range of observed temporal and spectral variation in masking present and proposed how masking models can be improved by incorporating time-based analysis of signals and the masking noise (Sills *et al.*, 2017). A critical ratio is the difference between the SPL of a pure tone just audible in the presence of a continuous noise of constant spectral density and the sound pressure spectrum level for that noise expressed in dB (ANSI, 2013).

Monitoring

To reliably assess and mitigate the impacts of hydrocarbon E&P activities on marine mammal individuals or populations, numerous source-pathway-receiver parameters must be understood. When information gaps are identified, such as the seasonality of a marine mammal population presence, the accuracy of acoustic propagation modeling results or the effectiveness of certain mitigation measures, monitoring studies can be implemented to fill these key knowledge gaps. The most common types of monitoring programs implemented as part of E&P operations are categorized according to the source-pathway-receiver model (Table 3).

Table 3: Overview of the types of monitoring conducted to understand relevance aspects of the source, pathway and receiver of marine sound and impacts on marine mammals.

Source	Sound source characterization Sound source verification
Pathway	Acoustic monitoring studies Propagation modeling verification Propagation model parameterization
Receiver	Abundance, density and distribution Systematic surveys (distance sampling) (aerial and vessel-based) Shore-based distribution surveys Mark-Recapture Photo-identification Passive acoustic monitoring Marine Mammal Observers Monitoring of mitigation efficacy Behavior Behavioral response studies Theodolite tracking Focal follow

Source

Sound Source Characterization Studies - Measurements of the acoustic characteristics of E&P sources are usually conducted at different distances from the source. As air gun arrays and drilling vessels are not point sources, the multiple sound sources (e.g., individual air guns) create a near field acoustic environment in which the sound field consists of complex interactions among the sound waves created by the individual sources. As the sound waves are not in phase, the complex interactions consist of constructive and destructive interference (Jiménez-Arranz *et al.*, 2017). At some distance away from the source, a far-field environment is developed in which the wave fronts from the individual sources add in phase and produce plane wave fronts (Richardson *et al.*, 1995). Acoustic monitoring is typically conducted in the far-field. As source levels are mostly provided at 1 m away from the source, far-field measurements are back-propagated to calculate the theoretical source levels at 1 m from the source. Environmental and physical parameters are required to accurately model source levels, which brings a degree of uncertainty when estimating source levels. Multiple measurements at different distances, therefore, results in a more accurate

estimate of the source level. For non-point sources such as air gun arrays and drilling vessels, back-propagated source levels are higher than actual measured levels because of the destructive interference of each gun and not all pressure peaks arrive at the receiver at the same time (Caldwell & Dragoset, 2000). So, whereas the effective source level predicts pressures in the far-field of the array that can be up to 260 dB peak re 1 μPa , in the near-field, the maximum pressure levels encountered are generally limited to between 220 and 230 dB peak re 1 μPa (Hildebrand, 2009). Numerous sound source characterization studies of seismic sources and drilling activities have been conducted to determine source levels, many of which were conducted in the Alaskan Beaufort and Chukchi Seas. Few peer-reviewed publications are available and most of these data are available in reports and grey literature (Jiménez-Arranz *et al.*, 2017).

Sound Source Verification Studies - Sound source verification (SSV) studies are conducted to determine the accuracy of modeling results. Some seismic good practice guidelines propose the use of an exclusion zone based on a fixed distance from the air gun array. For example, the Joint Nature Conservation Committee (JNCC, 2017) recommends a fixed exclusion zone of 500 m, which should be monitored prior and during ramp-up. If animals are observed within this zone, start of the survey must be delayed. In other jurisdictions, the air guns must also be shut-down when a marine mammal is observed in the exclusion zone, or when approaching this zone, *during* active air gun operation. Other guidelines propose the use of exclusion zones based on acoustic thresholds (Southall *et al.*, 2007; NMFS, 2000, 2016, 2018, ACCOBAMS, 2013). When acoustic thresholds are used, the exclusion zone radius around a source depends on the source configurations, depth of the source in the water, and environmental parameters such sound speed profile, water depth, bathymetry, and subsurface sediment or rock density. General assumptions about these variables are made during development of the propagation model. Sound source verification measurements are conducted to quantify the accuracy of the propagation model results and the estimated exclusion zone. SSV measurements are made by linearly deploying several acoustic recorders (2-5) at various distances from a source. In case of SSV to determine exclusion zones, the vessel will approach the array perpendicularly. Measurements at the broadside of a source are then used to determine the exact distance from the source to the relevant acoustic threshold by developing regression curves between measured sound levels at the different distances from the source (Figure 2). Racca *et al.* (2015) provided a detailed outline of an SSV experiment and how modeled exclusion zones are modified based on the outcome of SSV measurements. Aerts & Streever (2016) compared modeled and measured underwater sound isopleths conducted as part of seismic surveys in the Chukchi Sea, Alaska. They found a poor agreement between modeled and measured results that was thought to result from natural variability in the marine environment, the application of precautionary correction factors, and data interpretation in the generation of the modeled sound isopleths.

Figure 2: Schematic overview of a typical sound source verification experiment. In this example, 3 recorders are used (R1, R2, R3), though this number can vary. The farthest recorder is often placed at the expected location where an acoustic threshold (injury or behavior) is expected to occur to verify that modeled results are accurate.

Pathway

Propagation Modeling Verification Studies - SSV studies are mostly conducted to determine the radius of an exclusion zone around a sound source that is generally less than one km, but they can also be used to verify the accuracy of modeling results over larger distances (Martin *et al.*, 2017). The latter is not common, but it is occasionally done when there are areas of specific concern further away from the survey, such as breeding or feeding grounds of endangered populations of marine mammals (Racca *et al.*, 2015; Martin *et al.*, 2017). Because of the concern of potential impacts from a seismic survey in Baffin Bay on a summer resident population of narwhal in Melville Bay, Martin *et al.* (2017) modeled sound levels up to 100 km away from the air gun source. Acoustic recorders were deployed at various distances to verify the modeling results. It was found that pre-survey estimates of the received sound levels were three to seven dB higher than the levels measured at distances from 0.5 to 65 km away. Model parameters, such as sound speed profile, bathymetry, were adjusted that resulted in better alignment with differences of 0-4 dB. In special circumstances, sound source verification studies can also be done in real time. Racca *et al.* (2015) reports on a unique real-time sound verification program to ensure that the exposure levels of gray whales off Sakhalin, Russia, did not exceed the acoustic thresholds set for behavioral responses.

Model Parameterization Studies - Propagation modeling studies require accurate environmental data on depth, sound speed profiles, bathymetry, and subsurface density (Urlick, 1983). Seasonal changes in these parameters, such as water temperature, will influence the outcome of propagation models (Racca *et al.*, 2015). Oceanographic data can be collected in advance, or at the start of E&P activities, or may be available through long-term data collection programs. Sound speed

profiles are obtained by deploying a CTD (conductivity, temperature, depth) sensor that measures conductivity (salinity) and temperature as a function of depth. Salinity and temperature and pressure are used to determine the density of water, which influences sound propagation.

Receiver

Abundance, Density, and Distribution - Knowledge of the abundance, density, and distribution of marine mammals is needed to assess the vulnerability and conservation status of a population (Muir *et al.*, 2016; Bröker *et al.*, 2019). Insights to the abundance and distribution of marine mammal populations can be difficult to obtain, due to the remoteness, migration and distribution patterns, and cryptic behavior of different marine mammal species. Several techniques have been developed such as aerial and vessel-based line transect surveys (Buckland *et al.*, 2001), mark-recapture studies (Hammond, 1986, 1990) and, more recently, passive acoustic monitoring (PAM) (Marques *et al.*, 2009; Küsel *et al.*, 2011). Additionally, data on abundance and distribution are required to determine the impacts of human activities, such as harvesting or resource development, on marine mammal populations. During impact monitoring studies, these parameters (i.e., abundance and distribution) are typically assessed before, sometimes during, and after an activity (e.g., Muir *et al.*, 2015).

Systematic Surveys (distance sampling) - Systematic surveys of marine mammal populations are conducted to collect population abundance and distribution data. These surveys are typically conducted by humans on observation platforms, such as line-transect surveys from vessels or airplanes (Buckland *et al.*, 2001; Rekdal, *et al.*, 2015; Bröker *et al.*, 2019), or point surveys from shore-based stations (e.g., Gailey *et al.*, 2015; Muir *et al.*, 2015, 2016) using distant sampling methodologies as outlined in Buckland *et al.* (2002). More recently, surveys are also conducted using a combination of autonomous technology (unmanned aerial vehicles) still photography or video (e.g., Koski *et al.*, 2013, 2015; Bröker *et al.*, 2019). During systematic surveys, a pre-planned pattern is surveyed for presence of marine mammals. Correction factors are applied for availability (i.e., average time animals spend at the surface during which animals can be detected) and distance-dependent detection rates (i.e., correction for missed animals farther away from the track-line or observation point). The variance in the observational data is then used to estimate a confidence interval around the abundance estimate (Buckland *et al.*, 2001). The main advantages of aerial surveys over vessel-based surveys are (i) the ability to cover larger areas per unit time, (ii) reduced disturbance of animals, (iii) less dependence on sea state, and (iv) reduced cost as the charge rate for suitable vessels is typically high, especially in Arctic regions (Henkel *et al.*, 2007). Disadvantage of aerial surveys are (i) human safety concerns, (ii) higher dependence on weather conditions; for example, low cloud cover can prevent aerial surveys from flying at target observation altitudes while vessel-based surveys are not affected by low cloud cover as long as the horizon is visible, (iii) limits on the distance between the survey area and a shore-based landing strip, and (iv) fuel-limited survey effort when the survey area is far from land (Hodgson *et al.*, 2013), and (v) a narrower swath during aircraft-based surveys than during vessel-based surveys (Koski *et al.*, 2015).

Mark-Recapture - Mark-recapture studies are conducted to determine (changes in) abundance of a population. The basic concept of a mark-recapture effort is to sample and mark several individuals from a population, release them back into the population, with subsequent resampling of individuals to determine the proportion of marked individuals. The population estimate ($\hat{N}$) is determined by $(\hat{N}) = (M \cdot T) / R$, with M = number of marked individuals, T = total recaptured individuals and R = number of marked recaptures. The assumptions underlying these models are provided in Urian *et al.* (2015). Marking of marine mammals is done using different methods, such as photo-identification, genetics or tags. The most commonly used methodology is non-invasive through photo-identification, where individuals in a population are repeatedly photographed (seasonally and/or annually). Individuals can then be recognized by skin patterns such as pigment spot patterns and scars (Tyurneva *et al.*, 2008), fluke (Katona *et al.*, 1979), or the shape of dorsal fin (Würsig & Würsig, 1977; Würsig & Jefferson, 1990). The first identification equals the 'mark' of an individual, with subsequent identifications being the 'recaptures'. Individuals can also be 'marked' through their DNA profile or genetic footprint. This involves taking a tissue sample, often a skin biopsy, from which an individual can be distinguished based on mitochondrial haplotypes and microsatellite markers (Hammond, 1986; Palsbøll *et al.*, 1997; Palsbøll, 1999; Smith *et al.*, 1999; Rekdal *et al.*, 2015). A combination of photo identification and genetic identification mark-recapture efforts are also possible if skin samples are taken from individuals that have been photo-identified. Lastly, as pinnipeds can be approached on shore, branding or long-lasting tags can be applied on flippers to mark individuals (Pistorius *et al.*, 2000; Wilkinson *et al.*, 2011), although there is a risk of tag loss that will influence the outcome of mark-recapture efforts (Schwarz *et al.*, 2012).

Photo-identification - Recognition of individuals through photo-identification efforts are also used for numerous other objectives, which are summarized in Hammond *et al.* (1990). In addition to mark-recapture studies, a main purpose of photo identification is to determine reproductive rates and calf and adult survival rates, both relevant to monitor population dynamics (Bradford *et al.*, 2006). Additionally, results from photo identification studies provide insight into individuals' fine and large-scale migration patterns such as movement between feeding grounds (Tyurneva *et al.*, 2010), and migration between feeding and breeding grounds (Weller *et al.*, 2012). Inter and/or intra- annual changes in body conditions can be derived from photo-identification studies as well, which can be important to detect potential impacts of disturbance caused by E&P activities (Bradford *et al.*, 2008). Anthropogenic disturbance has the potential to influence the bio-energetic requirements of marine mammal individuals (Villegas *et al.*, 2015, 2017), making body condition a useful parameter to monitor.

Passive Acoustic Measurements - Passive acoustic monitoring (PAM) is used to monitor for presence/absence, as well as proximity, of marine mammal species (e.g., Heloise-Mouy *et al.*, 2017, Verfuss *et al.*, 2018) and has been conducted since the early 90s (Sousa-Lima *et al.*, 2013). Relatively novel methodologies have been developed to determine the size and density of cetacean

populations by using acoustic sensors to record vocalizations (Barlow & Taylor, 2005; Marques *et al.*, 2009; Küsel *et al.*, 2011). Most density estimation methods are based on estimates of the probability of detecting vocalizations as functions of distance (Küsel *et al.*, 2011). The number of acoustic cues (vocalizations) are then used to estimate cetacean densities by making assumptions on the probability of detecting cues, cue rates, and the proportion of false positive detections (Marques *et al.*, 2009). Acoustic tags are often applied to individual animals to obtain insights about cue rates.

The advantage of PAM over visual surveys is that marine mammals can only be visually detected in daylight and good weather conditions. Additionally, some species, e.g. beaked whales, are difficult to detect due to their long dive behavior. Especially in remote and inaccessible areas such as ice-covered areas PAM can have advantages (Frouin-Mouy *et al.*, 2017). Furthermore, visual surveys can be expensive due to cost associated with vessel or plane hire. A key disadvantage of PAM is lack of detection when a focal species is not vocalizing; sound production is a requirement for PAM to be successful. More information on passive acoustic monitoring systems and methods are provided in Mellinger *et al.* (2007) and Verfuss *et al.* (2018).

Marine Mammal Observers - During most seismic surveys, marine mammal observers (MMO), also referred to as protected species observers (PSO) in the USA, monitor for the presence of marine mammals around the seismic or drilling vessel. Depending on the country of operation, there are differences in the number of required MMO's during E&P activities, their role, and the level of training needed. Typically, they are tasked with conducting a pre-survey scan prior to activating the seismic air gun source, ensuring the exclusion zone is clear of marine mammals and sometimes other species such as sea turtles, before and during ramp-up. And, in most cases, MMOs monitor for presence of marine mammals in the exclusion zone during seismic acquisition. Upon observing animals in the exclusion zone before ramp-up or during ramp-up or acquisition, the MMO will make the air gun operator aware of the presence of marine mammals so that delay or a shut-down can be made. For this reason, MMO's have an important role in implementation of seismic survey monitoring and mitigation plans. In most surveys, one or two MMOs are on duty during seismic acquisition with shift limitations between 2-4 h. In addition to implementing mitigative actions, MMOs collect systematic data on observed marine mammal species, environmental conditions, and project activities. Although MMO data are not typically used to assess population abundance, this information provides useful presence/absence and distribution data of marine mammal species. Additionally, MMO data are analyzed to determine the effects of seismic surveys on marine mammal behavior, how well mitigative measures are applied, and the efficacy of mitigation measures (Stone, 2015a, 2015b). MMOs can effectively monitor a zone of approximately 2 km around a seismic vessel in suitable conditions. Monitoring is limited by poor weather conditions or nighttime when visual observations are not effective, in which case, passive acoustic monitoring is often used instead. Use of PAM during poor visibility conditions can be a regulatory requirement in a number of countries.

Behavioral Response Studies – The advantages and disadvantages of different types of behavioral responses studies, and key results from behavioral response studies to air guns were summarized in the section on Behavioral Responses, Disturbance and Stress.

Mitigation

E&P companies conduct environmental impact assessments (EIA) for most significant E&P activities, such as seismic surveys or drilling, in most regulated jurisdictions around the globe. The purpose of an EIA is to describe the activity, outline the regulatory framework and requirements, identify the environmental aspects, assess the single and cumulative environmental impacts, provide a plan to mitigate the identified risk, and assess if the residual risk is acceptable. Impacts are usually mitigated to meet regulatory established impact thresholds, or until the residual impacts are reduced to *As Low As Reasonably Practical* (ALARP) (IOGP, 2010; Petersen & Valeur, 2013). ALARP means that the amount of mitigative effort and thus the time, cost, and logistics associated with those mitigative measures should be in line with the assessed risks. If the risk to a marine mammal population is low, it is reasonable to apply less stringent mitigation measures, compared to when risks are high, which requires more mitigative action.

Various frameworks for risk assessments of E&P activities are available (Kyhn *et al.*, 2011, Wood *et al.*, 2012; DCE 2015, Nowacek *et al.*, 2013; NMFS 2016, 2018; Forney *et al.*, 2017). Additionally, there are numerous guidelines for mitigation of E&P activity impacts, both developed by the E&P industry (IOGP 2017) or by regulatory and environmental organizations (Prideaux & Prideaux 2015; JNCC, 2017). In addition to guidelines, agencies regulating E&P activities often prescribe what mitigative measures are needed to avoid and minimize possible impacts from E&P sound sources (Weir & Dolman, 2007; EPDC, 2008; DOC, 2013; DCE 2015; NMFS, 2016, 2018; DFO 2016).

A range of mitigation measures can be applied to address the impacts of E&P activities on marine mammals. These measures can be categorized based on the mitigation hierarchy, a concept first introduced by the International Finance Corporation (IFC, 2012). The different sequential steps in the mitigation hierarchy to minimize impacts of E&P activities are (i) avoidance, (ii) reduction, (iii) restoration, and, eventually (iv) offsetting (Figure 3).

Figure 3: The mitigation hierarchy with different measures to avoid and minimize impacts of E&P sound sources on marine mammals.

Whereas the third and fourth steps (restoration and offsets) in this mitigation hierarchy are being applied in terrestrial environments, the application of these steps in marine environments, specifically with regards to managing noise impacts related to marine mammals, are difficult to achieve (Jacob *et al.*, 2016; Milner-Gulland *et al.*, 2018). This is because both the impacts of E&P activities on marine mammal populations and the effectiveness of restoration and offsetting activities are challenging to quantify. Most mitigation measures currently applied belong in the first two steps of this mitigation hierarchy.

The following section provides an overview of the full suite of measures available for inclusion in marine mammal mitigation plans for E&P activities and brings together the current understanding of impacts and mitigations of marine sound from E&P activities. It is the author's view that mitigation plans should be developed in line with the assessed risk of the activity, i.e. effective and efficient mitigation plans are developed in line with the ALARP principle.

Avoidance

The most effective way of managing potential impacts of E&P activities on marine mammal populations is avoidance of overlap between activities and populations in space and time (Nowacek *et al.*, 2013; Bröker *et al.*, 2015). Avoiding impacts can be achieved when marine mammal populations are absent from the vicinity of exploration or production areas for part of the year. This can be the case when populations have migratory patterns between summer feeding grounds and winter breeding grounds, as is the case for most mysticetes (Nowacek *et al.*, 2015). Some odontocetes also follow annual migratory patterns, e.g. a narwhal population off west Greenland who resides in northern summer areas and overwinters in lower latitude areas (Heide-Jørgensen, 2003). When E&P activities can be scheduled for periods when populations are not present or only in low numbers, the potential impacts will be largely avoided. Avoidance of impacts can be conducted on a voluntary basis by E&P companies or can be directed by regulatory agencies. One example is described in Bröker *et al.* (2015), where a seismic survey was conducted near the summer feeding grounds of a critically endangered population of gray whales off Sakhalin in 2010. The primary mitigation measure was to complete the survey before the arrival of most individuals and cow-calf pairs. Another example relates to the previously mentioned population of narwhal that reside in the summer in Melville Bay, Greenland, and migrate to lower latitude toward the end of September and October. Due to concern over disturbance resulting in possible ice-entrapment, the Danish Centre of Environment made it a requirement that seismic survey campaigns be completed by 15 October (Kyhn *et al.*, 2011; Heide-Jørgensen *et al.*, 2013). In certain areas, temporal planning around presence of marine mammal populations can be challenging or impossible due to restrictive ice or weather conditions or the presence of marine mammals, or other sensitive marine species, year around. Avoidance of overlap between E&P activities and presence of marine mammal populations requires data in population dynamics such as feeding and breeding locations and seasonality, and migration patterns and timing.

Minimization

There are various mitigation measures that can be applied to minimize the potential impacts of E&P activities on marine mammals. Measures involve the reduction of activity-related sound levels, minimizing unnecessary high frequencies generated in seismic surveys, and ensuring that marine mammals are not exposed to sound levels potentially resulting in auditory injury.

Reduction of Activity-related Sound Levels - Sound source levels of air gun arrays increase with larger volume arrays. Sound source pressure levels must be of sufficient strength to illuminate the areas of industrial or scientific interest, typically at depths of 7 km or more (Gisiner, 2016). It is good practice to design arrays that have the lowest sound source pressure levels required to obtain satisfactory data, and not use excessively, unnecessarily large arrays. Arrays should also be designed in a way that maximizes downward propagation and minimal horizontal propagation. Explosives were used as the main energy source during marine seismic surveys until the mid-1960s (Fitch & Young, 1948; Richardson *et al.*, 1995). For several reasons, safety especially, explosives were replaced with water- and air-guns as the seismic source (Lugg, 1979; Hutchinson & Detrick, 1983). Water-gun pulses contain more high frequencies in comparison to airguns and are a good source for very high-resolution surveys but have relatively limited penetration (Hutchinson & Detrick, 1984; Richardson *et al.*, 1995). These days air guns are the main source used during hydrocarbon exploration, development, and production. This is because air guns have the optimal combination of lower cost, high source level, low-frequency sound, relatively low-pressure pulse rise-time (~5 ms) in comparison with chemical explosives (<1ms) and water-guns as related to concerns over barotrauma and better safety (Hutchinson & Detrick, 1983; Urick, 1983; Richardson *et al.*, 1995). An alternative source that has potential to replace air guns in certain situations is marine vibrators. Marine vibrators produce a continuous sound at lower source pressure levels, with the main advantage being the absence of medium and high frequencies (<250 Hz). Thus, the risk of auditory injury is much lower as compared to air guns. However, at present, it is not well understood how the risk of disturbance and/or masking caused by marine vibrators compares to air guns. Comparative risk assessments are currently underway to obtain greater insight to the environmental advantages of this alternative source (LGL & MAI, 2011). Marine vibrators have been used for hydrocarbon exploration but are not yet commonly used (Laws *et al.*, 2018). There are various efforts ongoing in the E&P industry to further advance this technology and make it commercially available (Feltham *et al.*, 2018).

A commercially available technology to reduce sound source pressure levels around stationary sources, such as pile driving or drilling rigs, are bubble/resonator curtains that are placed around a point source. Bubble curtains are commonly used around pile driving activities and are effective in reducing source levels by ~10-20 dB (Würsig *et al.*, 2000; Matuschek & Betke 2009; Lucke *et al.*, 2011). Bubble curtains can consist of free-flowing bubbles, encapsulated bubbles or resonator shields. At present, bubble curtains cannot be applied around moving sources, such as air gun arrays due to size, weight and drag, or at deeper depth due to higher pressures.

Minimize High Frequencies - Most of the energy in air gun pulses is in the 5-200 Hz bandwidth. However, air guns produce frequencies of up to 16 kHz (Landrø *et al.*, 2011; Martin *et al.*, 2017), which overlaps with the best auditory ranges of some odontocetes. These higher frequencies, i.e. above 200 Hz, have no utility for subsurface imaging due to their lower ability to penetrate the substrate. Minimizing high frequencies in air gun pulses is, therefore, an effective way of reducing potential injury and disturbance zones for odontocetes around an air gun array. Recent developments in air gun design have resulted in a commercially available air gun with reduced acoustic output at high frequencies, achieved by redesign of the mechanisms that controls the release of air (Coste *et al.*, 2014; Gerez *et al.*, 2015; Supawala *et al.*, 2017).

Pre-survey Marine Mammal Search - Prior to start of the air gun ramp-up sequence, a pre-survey search is typically conducted by MMOs to ensure no animals are in the direct vicinity of the array (see above). If animals are seen within the pre-defined exclusion zone, ramp-up or start of the array is delayed until the exclusion zone is cleared. Pre-survey searches are usually conducted for a minimum of 20-30 min., and up to 60-120 min. in deep-water where deep-diving marine mammal species may be present or in new locations under poor visibility conditions (DOC, 2013).

Ramp-up - Ramp-up, also called soft-start, is the systematic increase of acoustic output of a source over the course of 20-40 min. (Ainslie & von Benda-Beckman, 2013). The application of a ramp-up procedure is standard practice in most activities with risk of causing disturbance or thresholds shifts, such as pile driving and seismic surveys. In seismic surveys, this is achieved by starting with the smallest air gun in the array and gradually adding other air guns and/or increasing the pressure. The objective of ramp-ups is to reduce the likelihood of hearing damage or severe behavioral responses. The assumption behind ramp-ups is that exposure of marine mammals to lower sound levels results in movement away from the direct vicinity of air guns, thus preventing exposure to high sound levels when the array is fully operational (Weir & Dolman, 2007). Ramp-ups are usually conducted prior to the start of every acquisition line or when the array has been silent for a certain period (10-20 min.). Although the application of ramp-ups is included in all available seismic guidelines and regulatory requirements (Weir & Dolman 2007; DEWHA, 2008; DOC, 2013; ACCOBAMS, 2013; DCE, 2015; NMFS, 2016, 2018; DFO, 2016; JNCC, 2017), the way it is conducted varies widely and the efficacy of this mitigation measure is not entirely understood. The only systematic study conducted on efficacy of ramp-up of seismic air gun arrays was conducted by Dunlop *et al.* (2016), who studied responses of migrating Australian humpbacks to ramp-up by using an array of six air guns with the smallest being 20 in³. Dunlop *et al.* (2016) found that humpback groups increased their distance from the source; however, the initial level of the ramp-up was not found to be relevant, and neither was the source nor received level throughout the exposure phase. The presence of the source vessel without an active source was also found to have effect on humpback avoidance behavior. Despite these findings, Dunlop *et al.* (2016) concluded that a ramp-up procedure could be effective in

keeping groups away from the source as most groups changed movement to increase distance from the source vessel. Stone (2015a) analyzed 190.0 h of MMO and PAM data, with active source activity in 39% of the time. Based on 9,073 sightings or acoustic detections of marine mammals, comprising 124,024 individuals, it was concluded that the use of a ramp-up may be an effective measure. This was because fewer individuals were observed near the vessel during ramp-up and more animals were observed avoiding or traveling away from the seismic vessel. In a study on the effectiveness of ramp-up as part of sonar operations, it was found that ramp-up procedures before full-level sonar operations can reduce the risk of hearing thresholds shifts with marine mammals, but that their effectiveness depended strongly on the responsiveness of the exposed animals (Ainslie & von Benda-Beckmann, 2013; von Benda-Beckmann *et al.*, 2013, 2016). In the case of humpback whales, ramp-up was not found to be an effective mitigation measure to reduce the risk of physiological effects, as most whales did not exhibit a strong avoidance response to sonar signals (Wensveen *et al.*, 2017). This study also indicated that ramp-up of sonar reduces risk more effectively in situations in which animals are more responsive, e.g. when animals are in a non-feeding or reproductive state, suggesting that ramp-up is more effective in species that are more behaviorally responsive (Wensveen *et al.*, 2017).

Exclusion Zones - A key mitigation measure to reduce the likelihood of auditory damage due to exposure from high sound levels is the use of exclusion zones, also called injury, mitigation or safety zones (NMFS, 2016, 2018; JNCC, 2017). Exclusion zones are zones around a sound source that are monitored for presence of marine mammals by MMOs or passive acoustic monitoring systems. Exclusion zones in the E&P industry are mainly used during seismic survey operations, but occasionally also for other activities such as pile driving or drilling. The width of exclusion zones varies dependent on regulatory requirements, source levels, and species of concern. Exclusion zones around a seismic array can have either a fixed radius, e.g. 500 m around the source as recommended by JNCC (2017) and DEWHA (2008), or by modeled distances to regulatory acoustic thresholds. Acoustic thresholds for mitigation zones are based on peak pressure or m-weighted SELs (NMFS, 2016, 2018; Southall *et al.*, 2007, 2019). Some guidelines assume that animals naturally avoid the exclusion zones due to the presence of loud sound sources and do not require shut-down of the source during seismic acquisition (e.g., JNCC, 2017). Other guidelines and regulations require monitoring of exclusion zones during operations as well, including shut-down of the source upon detecting marine mammals within this zone during operations to avoid risks of auditory injury. Whereas exclusion zones are used in most seismic surveys to avoid auditory injury, use of exclusion zones to mitigate behavioral responses is not common in the E&P industry. Reasons for this include (i) the zones where potential behavioral disturbance occurs are too large to effectively monitor for presence of marine mammals, (ii) the number of shut-downs could be so large that the survey would be impossible to complete, and (iii) the lack of evidence that seismic surveys cause a decline in population size through disturbance or behavioral responses to individual animals as most responses appear to be of moderate severity (response score 4-5 for severity scoring in Southall *et al.*, 2007).

Use of behavioral exclusion zones have been applied when seismic surveys are conducted near critically endangered populations, near important feeding or breeding groups, or when there are multiple other disruptive anthropogenic activities are ongoing. Example of use of exclusion zones to mitigate for behavioral responses is provided in Johnson *et al.* (2007) and Bröker *et al.* (2015), who report on seismic operations near a small population of western gray whales off Sakhalin.

Use of Mitigation Air Guns - Line turns during seismic surveys can take several hours (Bröker *et al.*, 2015), during which the air guns are switched off. Some seismic guidelines recommend continued use of the smallest air gun array during these line turns, i.e. when the full array is not active, to continue to deter marine mammals away from the seismic vessel (DOC, 2013; DCE, 2015). The efficacy of this mitigation measure, however, has not been demonstrated and introduces additional acoustic energy into the marine environment. Additionally, this mitigation measure can be impractical for technical reasons as line turns are often used to depressurize and service the air gun arrays and may cause some safety concerns (Bröker *et al.*, 2015).

Restoration

Defining mitigation measures to restore the impacts of acoustic exposure to E&P sound sources are currently not applied, mainly due to difficulties in quantifying impacts and identifying action to negate those impacts after they may have occurred. One (theoretical) measure is to ensure that other potential sources of disturbance in the vicinity, such as other activities generating loud sound levels, are eliminated or minimized. In this way, exposed individuals can continue with their pre-disturbance activities, e.g. feeding, without experiencing additional and compounding impacts and their hearing systems can recover.

Offsetting

Offsetting of environmental impacts caused by marine sound is a new and unexplored field, in need of better guidelines and case studies. At present, there are no clear examples of offsetting efforts to mitigate impacts on marine mammal populations that are applied in the E&P industry. This is mainly due to the absence of significant impacts due to regulatory requirements to minimize potential impacts, and the difficulty in quantifying impacts and identification of appropriate offsetting measures. During various E&P activities, extensive monitoring and scientific programs have been implemented to enhance the understanding of marine mammal ecology and impacts of exploration activities on marine mammal populations. Whether monitoring, research or information gathering should be considered as an offset is an area of active controversy (Milner-Gulland *et al.*, 2018). Research could reduce uncertainty and promote innovation, which may be a prelude to later mitigation or avoidance activities once more is known about the biological setting (Milner-Gulland *et al.*, 2018). In terrestrial environments, where the concept of offsetting is more mature, research is not considered as an appropriate offset (Bull *et al.*, 2016). An example of offsetting impacts on marine mammal populations by E&P activities could be the initiation or funding of conservation programs focused on either reducing risks to a specific population

or species, or on the protection of the habitat that is important to that population or species. Theoretical examples of offset activities could be financial contributions towards funding of entanglement or ship strike reduction programs, or coast guard patrols and/or legal action against illegal and harmful fishing activities that could result in entanglement or bycatch of marine mammals (Rojas-Bracho & Reeves, 2013; Weller *et al.*, 2014).

International Guidelines

Numerous national and regional guidelines and legislative requirements have been developed to mitigate the potential impacts of E&P activities on marine mammal populations. An overview of available guidelines is provided in Weir & Dolman (2007). In absence of national guidelines or requirements, the JNCC guidelines are one of the most commonly applied guidelines in the E&P industry (JNCC, 2017). The International Organization of Oil and Gas Producers (IOGP) and the International Association of Geophysical Contractors (IAGC) jointly developed a recommended set of monitoring and mitigation measures for cetaceans during marine seismic survey geophysical operations (IOGP, 2017), which are quite similar to the JNCC guidelines. The JNCC guidelines have been criticized for lacking a scientific basis because of arbitrary exclusion zones size and lack of shut-down guidance (Wright *et al.*, 2015). The E&P industry, on the contrary, often tends to consider other guidelines as overly precautionary due to requirements for extensive monitoring and mitigation independent of the assessed risk to marine mammals. Most seismic surveys are different in terms of risks to marine mammal populations based on differences in area, airgun array size, species presence, animal abundance and distribution, duration, etc.; therefore, it is recommended that mitigation plans should be developed in line with those risks (Nowacek *et al.*, 2013). The E&P industry often refers to the ALARP approach as a way to align risks with proposed mitigations. Whereas for normal, low-risk, seismic surveys, the JNCC guidelines may be sufficient, for high-risk operations additional, more stringent mitigation measures may be necessary. Residual risks are those after the application of the mitigation measures that are assessed during environmental impact assessments. The outcome of these assessments is typically reviewed by the regulatory agencies to determine if they are acceptable, or that the activity is likely to result in unacceptable impacts. If the residual impact is deemed unacceptable, a survey may not be permitted, or additional mitigation measures may be required. Thus, as a minimum, the E&P industry must comply with the regulatory requirements. In the absence of regulatory requirements or when there is a need to go above and beyond the minimum requirements, the ALARP principle can be applied. This ALARP approach and inclusion of a risk-based element is currently insufficiently adopted in most guidelines, where often fixed sets of mitigation measures are proposed, independent of the potential impacts on marine mammal populations. Future guidelines and frameworks would benefit from applying a risk-based approach.

Recommendations for future studies and research and development

Because of concern over anthropogenic sound sources on marine mammal populations, the number of studies and research programs has increased over the past decades (Southall *et al.*, 2007, 2019; Cato *et al.*, 2013; NMFS, 2016, 2018; Costa *et al.*, 2016; Jiménez-Arranz *et al.*, 2017; Harris *et al.*, 2017). These efforts have enhanced our understanding of marine sound sources, propagation pathways, and impacts on marine mammals, and have improved our ability to manage these impacts. However, numerous key data gaps remain due to the multi-disciplinary and complex nature of this issue as well as an expansion in focus areas.

Whereas approximately 10-15 years ago the main concern was that air guns would result in mortality or injury to marine mammals, at present this focus has expanded in three-dimensions, i.e. from the perspective of (i) the source - primarily air guns but increasingly also includes, e.g. drilling, pile driving and other geophysical equipment (MacGillivray *et al.*, 2014; Austin *et al.*, 2018), (ii) the species groups - mainly marine mammals but increased focus on fish, invertebrates, and even plankton (McCauley *et al.*, 2017; Slabbekoorn *et al.*, 2019), and (iii) types of impacts - from mortality and injury to increased focus on disturbance and masking (Villegas-Amtmann, 2015, 2017; Erbe *et al.*, 2016; Costa *et al.*, 2016; McHuron *et al.*, 2018). Although our understanding of impacts of marine sound on marine mammals has expanded significantly over the years, some of the remaining priority knowledge gaps are described in the following section. This is not a complete assessment of all knowledge gaps and various stakeholders may have different views on priorities.

Source

Although some acoustic characterization studies of the full volume range of single air guns and air gun arrays output have been conducted (Tashmukhambetov *et al.*, 2009), higher resolution characterization over the full spectrum of frequencies containing acoustic energy is needed to verify and, if needed, modify source models (Ainslie *et al.*, 2016). Furthermore, a wider variety of sound source verification measurements of E&P sources would be useful, such as drilling rigs, subsea equipment, floating oil and gas processing facilities, and other geophysical equipment such as sparkers, boomers, and marine vibrators, to better assess impacts of such equipment on marine mammals. Additionally, development of alternative sound sources that could reduce impacts on marine life is valuable.

Pathway

If parameterized correctly, propagation models are quite good in predicting propagation over short to medium distance (up to several km). However, more long-range propagation modeling verification measurements in different environmental conditions are needed to determine the accuracy, and need to improve, acoustic modeling over long ranges (10-100 km.). Additionally, parameterization studies of acoustic models in different environments are required to improve the accuracy of the available acoustic propagation models.

Receiver

Audiograms and TTS measurements for a wider range of species are needed to depend less on interpolation between species, including development of novel methodologies to derive these in low-frequency species (mysticetes). Despite the extensive effort on weighting curve development, metrics and methods used for determination of injury thresholds, more effort is needed to further improve these weighting functions and injury thresholds, which should include metrics and methods that are easier to apply for assessment and mitigation of impacts of cumulative exposure. As cumulative SELs are calculated over prolonged periods of time (e.g., 24 h), an enhanced understanding of the role of hearing recovery between pulses, or period of silence within activities, is needed when applying this metric for injury thresholds, as recovery in periods of silence is currently not considered. Southall *et al.*, 2007 first proposed the use of the 24 h intermittency period to reset the SEL accumulation. Since then the use of shorter interval periods are being suggested that capture the periods with highest sound exposure levels (Finneran 2015; Martin *et al.*, 2019; Southall *et al.*, 2019), but this has not been adopted in regulations yet (e.g. NMFS, 2018). The need for the application of hearing weighting functions in the assessment and mitigation of behavioral responses, disturbance and masking has been recognized (Tougaard *et al.*, 2015, 2017; Kastelein *et al.*, 2019b), but additional experimental studies are needed to further mature this topic.

More controlled behavioral response studies using E&P sources on a range of different species would be beneficial to enhance our understanding of the severity of the responses, their duration, and the influence of other, non-disturbance, related aspects (e.g., context, behavioral state, etc.) on behavioral responses. The application of 3-D acoustic tags will be instrumental to detect fine-scaled changes in movement patterns as well as associated exposure levels. Outcome of these studies can then be used to further improve Population Consequences of Disturbance (PCoD) models to understand the “so-what?” aspect of behavioral responses, i.e. which type of responses, under what conditions (seasonality, duration, context, etc.), have a biological significance at a population level. These models could also be applied to better understand the issue of cumulative or aggregate impacts of multiple activities occurring in the same area, either at the same time or within the same season (Costa *et al.*, 2016; NAS, 2017).

Monitoring

The E&P industry would benefit from the development of autonomous monitoring technologies, such as autonomous operated camera-based aerial systems, or PAM arrays, to monitor (changes in) abundance and distribution of marine mammal populations in remote locations. Similarly, improved autonomous monitoring technologies to detect the presence of marine mammals near E&P activities, both in normal and poor visibility conditions, would be very useful to gain more insight on the impact of those activities on abundance, behavior, and distribution of marine mammals.

Mitigation

There are multiple efforts ongoing in the E&P industry to either modify the way air gun arrays are used or by developing new and alternative sources for exploration of hydrocarbon-bearing reservoirs with lower source levels, aimed at decreasing the likelihood of injury or disturbance of marine mammals, such as the development of marine vibroseis technology (Jenkerson *et al.*, 2018). Similarly, from a marine mammal perspective, the further modification of air gun arrays (and other acoustic sources) with less or no unnecessary medium and high frequencies (>200 Hz) will be beneficial, as it reduces the potential for impact to the medium and high frequencies species groups. For those E&P activities that generate sound without a purpose, such as drilling, piling and shipping, effective quieting technologies will be instrumental to reduce sound levels. Lastly, numerous mitigation measures are regularly applied during E&P activities such as seismic surveys, but for some of those measures the efficacy has not been assessed yet. This would be useful to ensure measures are indeed protective. Related to this is the need to enhance our ability to quantify impacts of E&P activities on marine mammal populations, if any. The concept of offsetting impacts on populations would benefit from being advanced as well. For example, in some cases, marine mammal populations may benefit more from conservation activities that are not related to E&P activities. In those instances, it may be more efficient from a conservation point of view to contribute towards the implementation of species-specific conservation activities instead of implementing an extensive monitoring and mitigation program.

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Chapter 3

A comparison of image and observer based aerial surveys of narwhal

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Abstract

From 25–30 August 2014 a double-observer line-transect survey was conducted over Melville Bay, home to one of two summering populations of narwhal (*Monodon monoceros*) off West Greenland. A total of 1,932 linear km was surveyed along 33 transects. In addition to using observers, the aircraft was equipped with two oblique cameras to capture a comparable data set. Analysts reviewed the images for narwhal sightings, which were then matched to the observer sightings. The objectives of the study were to determine advantages and disadvantages of the detection capabilities of both methodologies, and to conduct a comparative analysis of population abundance estimates. Correcting for the truncated detection distance of the images (500 m), the image analysts recorded more sightings (62) and a lower mean group size (2.2) compared to aerial observers (36 and 3.5, respectively), resulting in comparable numbers of individuals detected by both platforms (135 vs. 126). The abundance estimate based on the image sightings was 2,536 (CV=0.51, 95% CI: 1,003–6,406), which was not significantly different from the aerial observers estimate of 2,596 individuals (CV = 0.51; 95% CI: 961–7,008). This study supports the potential of using UAS for marine mammal abundance studies.

Keywords: abundance estimation, aerial surveys, Arctic, Melville Bay, *Monodon monoceros*, narwhal, line-transect survey, strip census, unmanned aerial systems, West Greenland

Introduction

Knowledge of the abundance, distribution and behavior of marine mammals are needed to assess the impacts of human activities, such as hunting or resource development, on their populations. Systematic surveys to collect marine mammal abundance and distribution data are typically conducted by human observers on observation platforms, such as vessels or airplanes (Buckland *et al.* 2001). In coastal areas where aerial surveys can be conducted, this is usually the preferred method of collecting data on marine mammal populations, although some exceptions occur, *e.g.*, Williams *et al.* (2017). For the purpose of marine mammal population distribution and abundance estimation, there are numerous advantages of aerial surveys over vessel-based surveys, including reduced disturbance, lower cost, and, in particular, the ability to cover much larger areas per unit of time (Henkel *et al.* 2007). One main disadvantage of aerial surveys is the risk to human safety, which increases in remote areas, like the Arctic, where an emergency response infrastructure is often lacking (Hodgson *et al.* 2013).

Over the last decade unmanned aircraft and sensor technologies have significantly improved and are being used in a wide range of emerging applications, including aerial surveys of nesting birds, and marine and terrestrial animals (Hodgson *et al.* 2013; Mulero-Pázmány *et al.* 2014; Chabot and Bird 2012, 2015; Chabot *et al.* 2015; Ratcliffe *et al.* 2015; Goebel *et al.* 2015; Patterson *et al.* 2016). The use of unmanned aerial systems (UAS) for marine mammal surveys is still in an exploratory phase, but usage is expanding rapidly (Koski *et al.* 2013, 2015; Hodgson *et al.* 2013). UAS equipped with high resolution video, or Digital Single Lens Reflex (DSLR) cameras, infra-red cameras, and/or other sensors, continuously taking pictures at fixed time intervals, is a potential alternative to manned aircraft surveys in high-risk, remote regions. In addition to increased safety in and access to remote areas, other advantages of UAS over manned aircraft are (i) potential lower cost (ii) possible higher detection rates due to the ability to dedicate more time to analyzing imagery (Koski *et al.* 2013), (iii) higher accuracy of location data, (iv) less disturbance to wildlife and, consequently, few to no behavioral responses (Koski *et al.* 2015, Smith *et al.* 2016), (v) potential improved line transect survey data due to lower responses to the presence of the survey platform (vi) the ability to conduct surveys when cloud ceilings are low, (vii) a lower environmental footprint due to greatly reduced fuel requirements (Hodgson *et al.* 2013, Koski *et al.* 2015), and (viii) longer endurance due to no observer fatigue. Some advantages of manned aircraft over UAS are (i) better ability to adapt to dynamic environmental conditions, *e.g.*, real-time adaptation of survey lines due to change in glacier fronts or fog, (ii) larger field of view to side and in front of aircraft resulting in a larger area being surveyed, and (iii) ability to collect additional off-effort data (*e.g.*, to identify species or collect additional species-specific data to strengthen the detection function).

Until recently, UAS were mainly used for monitoring populations in small areas (Jones *et al.* 2006, Chabot and Bird 2012, Hodgson *et al.* 2016, Patterson *et al.* 2016), in part because of restrictions preventing beyond-line-of sight flights, as well as the perception that human observers were superior to sensors in identification of detection cues for sightings. However, due

to improved sensor technology, unmanned surveys now have the capacity to cover areas similar in size to those surveyed by manned aircraft (Koski *et al.* 2013).

Aerial surveys of narwhal (*Monodon monoceros*), a medium sized Arctic odontocete, have been conducted off West Greenland since 1981 (Heide-Jørgensen *et al.* 1993, 2002, 2010, 2016; Heide-Jørgensen and Acquarone 2002; Heide-Jørgensen 2004). Aerial monitoring of narwhal populations is preferred as narwhals are sensitive to vessels and often occur in areas that are inaccessible to vessels (Finley *et al.* 1990, Heide-Jørgensen *et al.* 2010). The main objectives of these narwhal surveys are to determine the temporal variation in population size and assess the impacts of anthropogenic activities, such as the ongoing subsistence hunt that occurs off West Greenland (Heide-Jørgensen *et al.* 2010). Summer resident populations of West Greenland narwhals are found in Melville Bay and Inglefield Bredning (Heide-Jørgensen *et al.* 2010).

Historically, anthropogenic disturbances to narwhals in Melville Bay included hunting and disturbance by vessels. In recent years, hydrocarbon exploration activities have been conducted in Baffin Bay causing concern for disturbance to narwhals and the potential increase of ice entrapment (Heide-Jørgensen *et al.* 2013a). In the summer and fall of 2012, a large seismic survey campaign was conducted in four hydrocarbon exploration license areas in Baffin Bay, which is adjacent to Melville Bay, to explore for the presence of hydrocarbon-bearing formations (Frouin-Mouy *et al.* 2017, Martin *et al.* 2017). Acoustic modeling studies conducted prior to the seismic surveys indicated that sound generated by the four survey vessels would likely propagate into Melville Bay, and could potentially result in disturbance of narwhals (Martin *et al.* 2017). Narwhals are known to display behavioral responses to low sound level activities such as approaching vessels at relatively long distances (>50 km) (Finley *et al.* 1990). To quantify the impact of the seismic activities on narwhal distribution and abundance, aerial line-transect surveys, using four observers in fixed-wing aircrafts were conducted by the Greenland Institute of Natural Resources over Melville Bay in 2012 and 2014 (Heide-Jørgensen *et al.* 2013b, 2014). In 2014, the aircraft was also equipped with two high resolution DSLR cameras programmed to capture image data at regular time intervals. Images were analyzed postsurvey, with the purpose of comparing image sightings to human observer sightings. The objectives of this effort were to quantify (i) differences in absolute numbers of sightings, detection bias and distance estimation between image analysis data and real-time observer data, and (ii) the difference in narwhal abundance estimates between image analysts and aerial observers. Although studies comparing marine mammal detections by image analysts and aerial and land-based observers have been conducted before (*e.g.*, Koski *et al.* 2013, Hodgson *et al.* 2017), this is the first comparison of population estimates derived from both image and aerial observer data.

Methods

Survey Procedures

A fixed-wing twin-engine aircraft (DeHavilland Twin Otter) was used to conduct an aerial line-transect survey over Melville Bay from 25–30 August 2014. The surveyed transects traversed an area of 14,821 km², between 74.30° and 76°N (Figure 1). Target altitude and speed were 213 m (700 ft) and 168 km/h (90 knots), respectively. The study area was divided into four strata, with transects aligned east-west in the two southern strata and north-south in the two northern strata. Thirty-eight transects, covering 1,790 linear km, were systematically placed from the coast to offshore areas crossing significant bathymetric gradients (Figure 1). Transects were spaced closer together, increasing survey coverage, in the Northeast and Central strata, where narwhal abundance was expected to be higher based on previous surveys (Heide-Jørgensen *et al.* 2013). The planned survey protocol was, each day, to survey every other line.

Figure 1: Survey strata and transects designed for the aerial survey in Melville Bay from 25-30 August 2014. Transects that were not surveyed, or two or three times, are marked in blue, green or red, respectively. All black transects were surveyed once.

Aerial observer data collection

Four aerial observers conducted a double-observer experiment, with the two front observers (Observer pair 1) recording data independently of the two rear observers (Observer pair 2). A long-range fuel tank was situated between the front and rear observers preventing cueing of sightings. Observers were instructed to scan the water surface up to one kilometer ahead of the aircraft and abeam out to the horizon, but to concentrate their search effort along the track line; bubble windows enabled observation of the track line below the aircraft. Sightings of narwhals, declination angles to sightings and group size were recorded on hand-held dictaphones when the animals came abeam. A group was defined as multiple individuals within three body lengths or less from one another. Beaufort wind force was recorded at the start of each transect and when conditions changed. GPS data were automatically logged separately to a GPS-recorder.

Aerial imagery collection

Two autonomously operated Nikon D800 DSLR 36.3-mega pixel full-frame cameras equipped with 21 mm $f2.8$ Zeiss lenses were mounted with the long axis of the camera sensor perpendicular to the trackline, and obliquely angled 27° left and right of the track line in the belly port of the aircraft. Both cameras had a full frame sensor ($35.9\text{mm} \times 24\text{mm}$) and were set to take an image every 3 s, equivalent to an image every 140 m. This provided overlapping coverage in 54.9% of the trackline, *i.e.*, on average narwhal sightings could be seen in two consecutive images in 54.9% of the sightings on the trackline. Overlap at the outer edge of the image was much larger, and narwhals could potentially be seen in a maximum of 4.4 consecutive images. At the survey altitude of 213 m, each image had an overlap of 51 m on either side of the center line below the aircraft and covered an area out to 515 m from the center line, for a total swath of 1,030 m. One pixel on the water on the center line was 3.9 cm wide (213 m from the camera) and 9.8 cm wide at the outer edge of the frame (558 m from the camera), providing adequate resolution to detect individual narwhals throughout the image. Images were truncated at 500 m. A GPS logger and geo-tagger were used to receive and insert GPS coordinates and survey altitude into the metadata of each image. No corrections of image swath width for aircraft pitch and roll were attempted.

Abundance estimates using aerial observer data

Duplicate sightings (animals seen by both Observer pair 1 and 2) were determined postsurvey and were based on the time, distance from the track line, and group size of the sightings. Group size and perpendicular distance from the track line were averaged for duplicate sightings when these values were not identical. The declination angle to sightings recorded when animals were abeam was converted to radial distances using the equation:

$$\text{distance (d)} = h \cdot \tan(90 - \alpha),$$

with h being the survey altitude (213m) and α the declination angle of a sighting.

Following the methodology described by Heide-Jørgensen *et al.* (2010), MRDS, a combination of Mark Recapture and Distance Sampling models was used to estimate narwhal abundance in Melville Bay based on the visual survey (Laake and Borchers 2004). Typically, distance sampling (DS) methods (Buckland *et al.* 2001) are applied to derive detection probability away from the track line while assuming that detection on the track line is certain (denoted by $g(0) = 1.00$). When this assumption is not met, double-platform surveys can be used to estimate the actual detection probability on the track line using mark-recapture methods. Narwhal detections by the front observers served as a set of trials in which a success was defined as detection by the rear observers (duplicate), and *vice versa* and the detection probability on the track line was estimated by analysis of trials and duplicates. The detection function for the reduced probability of detecting an animal as the distance from the track line increases, $f(0)$, was estimated from the perpendicular distances using DS (Heide-Jørgensen *et al.* 2010).

Mark-recapture estimators are biased by unmodeled heterogeneity in detection/capture probability; this makes it important to model the effect of all variables that affect detection probability on double-observer distance sampling surveys (Borchers *et al.* 2006). As some potentially important variables might not be recorded or observed during a survey, sources of heterogeneity may remain. For this reason, a point-independent model (estimator based on the assumption that detections were independent only on the track line) was chosen over a full-independent model (estimator assuming that detections were independent at all perpendicular distances) (Borchers *et al.* 2006, Heide-Jørgensen *et al.* 2010). To incorporate the point independence assumption, both a multiple covariate distance sampling (DS) detection function for combined platform detections (Marques and Buckland 2004) and a mark-recapture (MR) detection function to estimate detection probability at the track line were used. The MR detection function is the probability that an animal at a given perpendicular distance x with covariates z , was detected by an observer q ($q = 1$ or 2), given that it was seen by the other observer, which is denoted by $p_{q13-q}(x, z)$. It is modelled using a logistic form:

$$p_{112}(x, z) = p_{211}(x, z) = \frac{\exp\{\beta_0 + \beta_1 x + \sum_{k=1}^K \beta_{k+1} z_k\}}{1 + \exp\{\beta_0 + \beta_1 x + \sum_{k=1}^K \beta_{k+1} z_k\}},$$

where $\beta_0, \beta_1, \dots, \beta_{K+1}$ represent the parameters to be estimated and K is the number of covariates other than distance. Note that if observer is included as an explanatory variable, then $p_{112}(0, z)$ will not be equal to $p_{211}(0, z)$. The intercepts (*i.e.*, at $x=0$) of $p_{112}(0, z)$ and $p_{211}(0, z)$ are combined to estimate their detection probability on the track line by at least one observer.

For the DS model, both half-normal and hazard-rate functions were initially fitted with no covariates (apart from perpendicular distance) and then covariates were included *via* the scale parameter (Marques and Buckland 2004). The available covariates were group size, side of the aircraft (left and right), Beaufort wind force (0, 1 or 2), and time to next sighting (<10 or >10

s). Group size was also included as a factor variable with three levels to represent group sizes of 1, 2–5 whales, and more than 5 whales. The same covariates were included in the MR model, in addition to a variable indicating observer pair (1 and 2). Akaike's Information Criterion (AIC) and goodness of fit tests were used for model selection.

Density ($\hat{D}_i$) and abundance ($\hat{N}_i$) of individual animals in a stratum were obtained using

$$\hat{D}_i = \frac{1}{2WL_i} \sum_{j=1}^{n_j} \frac{S_{ij}}{\hat{p}_{ij}},$$

and

$$\hat{N}_i = A_i \hat{D}_i,$$

where S_j is the recorded size of group j , A is the size in km^2 of the stratum, W is the truncation distance (1300m), L is the total effort in km, n is the number of unique detections and p is the estimated probability of detecting group j (perception bias). For variance estimation of $\hat{N}_i$, the method developed by Innes *et al.* (2002) was applied using the estimator R2 in Fewster *et al.* (2009). In order to account for the estimated availability bias ($\hat{a}$), corrected abundance ($\hat{N}_c$) was estimated by

$$\hat{N}_c = \frac{\hat{N}}{\hat{a}}$$

Parameter $\hat{a}$ is the estimated proportion of time animals are available for detection. The coefficient of variation (cv) of $\hat{N}_c$ was given by

$$cv(\hat{N}_c) = \sqrt{cv^2(\hat{N}) + cv^2(\hat{a})}$$

The assumption was made, in both the MRDS model for aerial observer data and the CDS model applied on the image analysts' data, that there was independence between the component variables (encounter rates, detection components, and group size).

An availability correction factor of 0.22 ($CV = 0.09$) was observed based on two female narwhals captured in nets and tagged with satellite-linked time depth recorders in Melville Bay in 2007 (Heide-Jørgensen *et al.* 2010). Additionally, as detection of marine mammals at the surface from a passing plane is not an instantaneous process, an additional correction factor was applied to account for the probability that the animal was at the surface on or near the track line taking into consideration the surfacing and dive behaviors (Thomas *et al.* 2010, Heide-Jørgensen and Laidre, 2015). The correction factor was estimated as following (Eberhardt 1978):

$$g_a(0) = \frac{s}{s+u} + \frac{t}{s+u} = \frac{s+t}{s+u}$$

where u is the average time spent submerged (length of dive), s is the average time at the surface during a dive cycle, and t represents the duration of the period when a surfaced animal would be

visible to an observer (Eberhardt 1978). Therefore, $s/(s+u)$ is the probability that the whale will be at the surface when its location first comes into visual range (0.22, CV = 0.09), and $t/(s+u)$ is the probability that the whale will surface while its location is in visual range. A viewing area of 1 km ahead of the aircraft was assumed in the estimation of t , equivalent to 21 seconds. This resulted in an availability correction factor of 0.257 for the aerial observers.

Confidence intervals for the abundance estimate were calculated using the log-based method described in Buckland *et al.* (2001):

$$\hat{D}/C, \hat{D} * C$$

with

$$C = \exp \left[z_{\alpha} \cdot \sqrt{\widehat{var}(\log_e \hat{D})} \right]$$

and

$$\widehat{var}(\log_e \hat{D}) = \log_e \left[1 + \frac{\widehat{var}(\hat{D})}{\hat{D}^2} \right]$$

where z_{α} is the critical value of Student's t-distribution at $\alpha = 0.05$.

Abundance estimates using image analysis data

On-effort images were reviewed by a team of six image analysts using a detailed manual analysis method to detect narwhal sightings. Imagery was reviewed on 30-inch monitors with a 2,560 x 1,600 screen resolution using Adobe Photoshop CS 6 extended. Each image was viewed at full 7,360 x 4,912 (100%) resolution and ~1/18th of the image was visible on screen at a time. Analysts recorded the location of each sighting within the image (x and y coordinates) and combined with the angle of the camera and survey altitude, the perpendicular distance from the track line was calculated by using the same formula applied to the aerial observer data, with α being the calculated depression angle of the sighting minus the angle from the camera to the near edge of the image. A group was defined as multiple individuals within 5 body lengths of each other.

Narwhal sightings identified in the digital imagery were evaluated by an independent panel of three senior analysts to confirm species and group size. Only narwhal sightings considered 'certain' were included in the analysis. More details on the image analysis methodology are provided in Koski *et al.* (2013).

For the development of an abundance estimate of narwhals in Melville Bay using image data, Conventional Distance Sampling (CDS) (Buckland *et al.* 2001) was first considered. A chi-square goodness-of-fit test was used to determine whether the detection function was flat across the truncated area of observation (500 m). This test indicated that was no significant difference in the probability of detection across the observation distance (Appendix 1). This was mainly because the resolution at the outer edges of the images was sufficient to detect the narwhals, and image analysts had sufficient time to detect narwhal. Therefore, the image data set was analyzed as a strip census. Density, encounter rate, group size, and abundance were estimated for each stratum containing narwhal sightings.

Density ($\widehat{D}_i$) and abundance ($\widehat{N}_i$) of narwhals in each stratum were estimated using

$$\widehat{D}_i = \frac{\sum_{i=1}^k n_i}{\sum_{i=1}^k X_i},$$

$$\widehat{N}_i = A_i \widehat{D}_i,$$

where k is the number of transects in stratum i , n is the number of detected individuals in stratum i , X_i is the area covered by the images in each transect (km²) and A_i is the total area of each stratum.

The average density was determined by

$$\widehat{D} = \frac{\sum_v A_i \widehat{D}_i}{A},$$

where V is the number of strata. The standard error for animal density was estimated using Buckland *et al.* (2015):

$$se(\widehat{D}) = \frac{se(\frac{n}{L})}{2w},$$

with

$$se \frac{n}{L} = \sqrt{\frac{K}{L^2(K-1)} \sum_{k=1}^K l_k^2 \left(\frac{n_k}{l_k} - \frac{n}{L} \right)^2}.$$

The average density ($\widehat{D}_i$) in the survey area was calculated and multiplied with the total survey area to determine the abundance of narwhals ($\widehat{N}$) in Melville Bay. Similar to the abundance estimates using aerial observer data, an availability bias ($\hat{a}$) correction of 0.22 (CV = 0.09) was applied. Corrected abundance was estimated by

$$\widehat{N}_c = \frac{\widehat{N}}{\hat{a}}.$$

Confidence intervals were derived using the log-based method as in Buckland *et al.* (2001).

Comparison of aerial observer and image sightings

To ensure the same pool of narwhal sightings were available for detection, aerial observer sightings were truncated at 500 m to correspond with the swath coverage captured in the images. The remaining aerial observer sightings were matched with image sightings using time of sighting, perpendicular distance from the track line, and group size and composition. There were considerable differences between the aerial observer and image sightings data, and two analysts independently completed the matching process before comparing results. Match discrepancies

were resolved by collectively determining the best available match.

For matched aerial observer and image sightings, a Wilcoxon signed-rank test for paired samples was used to determine differences in group size and perpendicular distance. Differences in group size and perpendicular distance for all aerial observer and image sightings (*i.e.*, not just matched sightings) were also examined using the Mann-Whitney Test for two independent samples. These comparisons were also conducted after truncating the aerial observer sightings at 500 m to correspond with the truncated swath width covered by the images, ensuring the same pool of narwhals were available for detection by both image analysts and aerial observers.

A $2 \times 2 \chi^2$ test was used to determine differences in total numbers of sightings and the number of individual narwhals, both with and without truncation of aerial observer data at 500 m. The $2 \times 2 \chi^2$ test was conducted with the expected value = (variable image + variable aerial observer) / 2. The degree of freedom was one and differences were considered significantly different if $P < 0.05$.

The population abundance estimates derived by using both aerial observer and image data were compared using the method described in Buckland *et al.* (2001) to obtain an approximate t -statistic, which was tested against a significance level of $\alpha = 0.05$:

$$T = \frac{(\hat{N}_1 - \hat{N}_2) - (N_1 - N_2)}{\sqrt{\widehat{var}(\hat{N}_1 - \hat{N}_2)}}, \sim t_{df}$$

where

$$df \simeq \frac{\{\widehat{var}(\hat{N}_1) + \widehat{var}(\hat{N}_2)\}^2}{\{\widehat{var}(\hat{N}_1)\}^2/df_1 + \{\widehat{var}(\hat{N}_2)\}^2/df_2},$$

using the null hypothesis $H_0: N_1 = N_2$, with substituting $N_1 - N_2 = 0$.

Results

Of the 38 planned transects, five were not completed due to weather conditions and fuel limitations, seven transects were surveyed two times, and two transects were surveyed three times. This resulted in the completion of a total of 44 on-effort transects covering 1,932 km (Table 1) out of the planned 1,790 km (Figure 1). Image analysts reviewed 20,756 on-effort images and an additional 180 off-effort images. Six analysts conducted detailed manual analysis of these 20,936 images image over a period of ~1,800 h.

Narwhal sightings were clumped in the Northeast and Central strata (Figure 2). No narwhals were detected by either image analysts or aerial observers in the Northwest or South strata (Table 1).

Figure 2: Narwhal sighting locations in the Melville Bay survey area in 2014 recorded by aerial observers in real-time and identified by analysts in digital imagery. Most of ‘observer only’ sightings are detections beyond the area covered by images (i.e., beyond 500 m from the trackline). The image of ice distribution was of 30 August 2014. We acknowledge the use of imagery from the NASA Worldview application (<https://worldview.earthdata.nasa.gov/>) operated by the NASA/Goddard Space Flight Center Earth Science Data and Information System (ESDIS) project.

Narwhal sightings by aerial observers and image analysts

The on-effort aerial observers identified 63 sightings of 227 individual narwhals. The mean group size was 3.6 individuals per group (CV = 0.72). The mean perpendicular distance of sightings from the track line was 580 m (CV = 0.74) (Table 2). The front pair of observers (Observer pair 1) made 54 sightings of 218 individuals (mean group size = 4.0). The rear pair of observers (Observer pair 2) recorded 31 sightings of 87 individuals (mean group size = 2.8). Twenty-two groups of narwhals were recorded by both Observer pair 1 and 2 (duplicate sightings), and 41 sighting were unique (observed by either Observer pair 1 or 2). Pairwise testing of declination angles and group size showed no systematic bias in duplicate sightings between observer pairs ($p = 0.30$ and $p = 0.26$ for declination angles and group size, respectively). Mean declination angle and group size estimates were therefore used in the abundance estimates and for comparison with image sighting data.

Image analysts identified a total of 62 sightings of 135 individuals, which were confirmed by the review panel. The mean group size was 2.2 (CV=0.77). Images covered an area up to 515

m from the track line, and the images were truncated at 500 m – although no sightings were made between 500 – 515 m. The mean perpendicular distance of sightings to the track line was 227 m (CV=0.58). The CDS detection function, and chi-square goodness-of-fit tests (Appendix 1) suggested that probability of narwhal detection was not significantly different from equal over the full range of aerial image coverage. Although the probability of detection over the full range of detections was not found to be different, the number of detected groups was higher around 150 m (Appendix 2), which was consistent with aerial observations (Figure 3).

Comparison of aerial observer and image sightings

Matched sightings

Two independent analysts matched aerial observer and image sightings using time, perpendicular distance, group size, and group composition, and obtained poor results. Twenty-eight matches were made from a combined pool of 70 on-effort observer and/or image sightings recorded within 500 m of the track line (Table 2). Values for both the mean group size and the perpendicular distance from the track line in these 28 paired sightings were different (Wilcoxon Signed-Rank for paired samples, $P < 0.001$ for both group size and perpendicular distance), indicating observers and analysts estimated group size and distance differently or that these were not true matches.

All sightings

The total number of on-effort image sightings (62) was not significantly different from the total number of on-effort aerial observer sightings (63) ($\chi^2 = 0.098$, $p = 0.93$). However, both the mean group size and the total number of individuals were different (Mann-Whitney test, $P < 0.001$; $\chi^2 = 22.25$, $P < 0.001$) (Table 2). Although the mean group size of the back and front observer pairs was not different, they were both individually tested against the mean group size determined for the image sightings. The group size of both observer pairs was larger compared to the image group size (Mann-Whitney test, $P < 0.001$ for both pairs). The mean perpendicular distance for image sightings (227 m, CV=0.61) was significantly smaller than that calculated for aerial observer sightings (580 m, CV=0.74) as the perpendicular field of view of analysts was considerably smaller than the aerial observers (515m *vs.* >2,000 m) (Mann-Whitney test, $P = <0.0001$).

Table 1: Summary of survey effort in the four strata during aerial surveys conducted in Melville Bay from 25–30 August 2014. * = including 180 off-effort images that were not used in the analysis. Ind. = individuals.

Stratum	Area (km ²)	Planned/ completed Transects (no.)	Length of surveyed transects (km)	Analyzed images*	Image			Aerial observers			Aerial observers (truncated 500m)			
					No. of sightings	No. of ind.	Ave. group size	No. of sightings	No. of ind.	Ave. group size	No. of sightings	No. of ind.	Ave. group size	
NW	6,376	5 / 4	226	2,066	0	0	0 (0)	0	0	0 (0)	n (CV)	0	0	0 (0)
NE	2,076	11 / 12	468	6,572	23	49	2.1 (0.95)	15	39	2.6 (0.77)	13	32.5	2.5	0.76)
C	2,621	9 / 18	663	8,193	39	86	2.2 (0.73)	48	188	3.9 (0.69)	23	93.5	4.1	0.61)
S	3,748	13 / 10	575	4,105	0	0	0 (0)	0	0	0	0	0	0	0
All strata	14,821	38 / 44	1,932	20,936	62	135	2.2 (0.77)	63	227	3.6 (0.72)	36	126	3.5	0.69)

Table 2: Summary of sightings by image analysts and/or aerial observers, with and without truncation at 500 m. Where both aerial observer pairs had the same sighting with different group size or perpendicular distance estimates, an averaged value was used.

	Sighted by image analyst	Sighted by observer	Only sighted by image analyst	Only sighted by observer	Sighted by image analyst and observer	Sighted by image analyst and/or observer
<i>No truncation</i>						
No. of groups	62	63	34	35	28	97
No. of animals	135	227	62	124	88	274
Average group size	2.2	3.6	1.8	3.5	3.1	2.8
Average distance	227	580	237	839	329	454
<i>Truncation = 500 m</i>						
No. of groups	62	36	34	8	28	70
No. of animals	135	126	62	24	88	173
Average group size	2.2	3.5	1.8	3.0	3.1	2.5
Average distance	227	269	237	329	234	247

Sightings with 500 m truncation

Aerial observer sightings were truncated at 500 m to align with the maximum detection range available to the image analysts due to the swath covered by each image (Table 2). The difference in number of sightings between image analysts ($n = 62$) and aerial observers ($n = 36$) was significant ($\chi^2 = 6.9$, $P = 0.008$). However, no significant difference was found between the total numbers of individuals observed by image ($n = 135$) and aerial observers ($n = 126$) ($\chi^2 = 0.31$, $P = 0.58$). This was because the mean group size of the image sightings (2.2, $CV = 0.77$) was smaller than the mean group size of aerial observer sightings (3.6, $CV = 0.67$) (Mann-Whitney test, $P < 0.01$). There was no significant difference in the mean perpendicular distance from the track line between the aerial observer (269 m) and image (227 m) sightings (Mann-Whitney test, $P = 0.18$).

Abundance estimate using aerial observer sightings

The detection function and perception bias estimates calculated for the aerial observer data set were based on mark-recapture methods using independent sightings recorded by two observer pairs (Figure 3). In the MRDS model, both a half-normal key functional form and a hazard-rate form were explored. The half-normal key functional form was selected based on the lower AIC with the distance detection range fixed at 0–1,300 m (Table 3). Appendix 3 provides an overview of all developed models. The final DS model had distance from the track line and Beaufort wind force as explanatory variables. The MR model had distance from the track line, observer pair, and group size (with three classes) as explanatory variables (Model 1, Table 3). The $g(0)$ for Observer pair 1 was 0.90 ($CV = 0.051$), which was higher than for observer pair 2 (0.75 ($CV = 0.08$)). The combined $g(0)$ was 0.97 ($CV = 0.022$).

Figure 3: Detection functions for Observer pair 1 (left panel) and Observer pair 2 (right panel) during aerial surveys in Melville Bay from 25–30 August 2014. Data are truncated at 1,300 m.

The detection function using detections by both observer pairs is provided in Figure 4. Use of the selected model (which included 26 off-effort group sightings to strengthen the detection function), and correcting for availability and perception bias, resulted in a total narwhal abundance estimate of 2,596 individuals (95% CI = 961.1–7,007.8; $CV = 0.51$).

Figure 4: Detection function plot of chosen DS model when sightings of both aerial observer pairs were pooled. Intercept obtained from the MR model. The solid black line indicates the probability detection function from the DS model and the open symbols indicate the probability of each detection given its perpendicular distance and other covariate values.

Table 3: AIC values after fitting explanatory variables to the DS and MR models. The final model chosen, Model 1, is given in bold and 'ΔAIC' indicates the difference between the chosen model and the specified model. HN indicates a half-normal form and HR indicates a hazard-rate form for the DS model. The explanatory variables are perpendicular distance (D), group size (S), group size as a factor with three classes (1, 2–5, and ≥6 narwhals) (S3), Beaufort (BF), side of airplane (SP), observer pair (O), and time to.

Model	DS model	MR model	No. of parameters	AIC	ΔAIC
1	HN: D + BF	D + O + S3	5	1330.91	0
2	HN: D + BF	D + O + S	5	1332.81	1.90
3	HN: D + BF + S3	D + O + T	6	1333.10	2.19
4	HN: D + BF	D + O	4	1333.50	2.59
5	HN: D + BF + S3	D + O	5	1335.08	4.17
6	HR: D + BF	D + O + S3	5	1336.97	6.06

Table 4: Summary statistics of survey results and narwhal abundance estimates from surveys conducted in Melville Bay, West Greenland from 25–30 August 2014. Off-effort sightings by the aerial observers were only included in modeling of the detection function. Strata without narwhal sightings were excluded from this table (*i.e.*, south and northwest). Abundance estimates are corrected for availability bias with $\hat{a}$ (0) being 0.257 for the aerial observer sightings and 0.22 for the image sightings. Aerial observer sightings were truncated at 1,300 m. CV values are given in parentheses. Ind. = individuals.

Platform	Stratum	Encounter rate (groups/km)	Encounter rate (ind./km)	Mean group size	Uncorrected density of groups (groups/km ²)	Uncorrected density of ind. (ind./km ²)	Uncorrected abundance of individuals	Abundance of individuals corrected for availability bias
Aerial observers	Northeast	0.032 (0.86)	0.084 (0.78)	2.6 (0.20)	0.046 (0.93)	0.115 (0.90)	300.7 (0.89)	1,171.0 (0.90)
	Central	0.068 (0.50)	0.261 (0.53)	3.8 (0.11)	0.046 (0.53)	0.177 (0.52)	366.5 (0.52)	1,426.1 (0.53)
	All strata	0.053 (0.41)	0.187 (0.44)	3.5 (0.10)	0.046 (0.58)	0.142 (0.50)	667.2 (0.50)	2,596.1 (0.51)
Images	Northeast	0.049 (0.94)	0.105 (0.92)	2.1 (0.91)	0.049 (0.94)	0.105 (0.92)	217.8 (0.92)	990 (0.93)
	Central	0.059 (0.70)	0.130 (0.61)	2.2 (0.71)	0.059 (0.70)	0.130 (0.61)	340.0 (0.61)	1,545.5 (0.61)
	All strata	0.055 (0.55)	0.119 (0.50)	2.2 (0.78)	0.055 (0.55)	0.119 (0.50)	557.8 (0.50)	2,535.5 (0.51)

Abundance estimate using image sightings

CDS models were developed for the image sightings using both groups and individuals as a unit for sightings (Appendix 2). As the detection function appeared to be flat across the range of detections (Appendix 1), a strip census was applied instead. Based on the image data, a total of 557.8 individuals were estimated to occur in Melville Bay (Table 4). After correcting for availability, the strip census estimate of narwhal abundance was 2,536 individuals (CV=0.51, 95% CI:1,003–6,406).

Comparison of image and aerial observer abundance estimates

The applied methodology to estimate abundance of narwhal in aerial images (strip census) was different than the methodology used for the aerial observers' sightings (MRDS). The detection range in the images was also different compared to that of the observers (515 m *vs.* >2,000 m). Despite these differences the Melville Bay narwhal abundance estimates calculated for the two data sets were remarkably similar, and only differed by 2.4%. The image abundance estimate of 2,536 individuals (CV=0.51, 95% CI: 1,003–6,406) was not significantly different than the aerial observer abundance estimate of 2,596 individuals, (CV = 0.51; 95% CI: 961–7,008) ($P = 0.97$).

Discussion

Models applied for image and observer data

The main objective of narwhal aerial surveys over Melville Bay is to monitor the population dynamics and to determine impacts of anthropogenic activities such as hunting and hydrocarbon exploration on the Melville Bay narwhal population. Accurate population abundance estimates are required to draw conclusions on potential impacts. Despite using different methodologies,

both platforms of observations had sufficient narwhal sightings to provide similar estimates of the abundance of narwhal in Melville Bay. The selected covariates in the aerial observer MRDS model suggest that sighting probability increased with group size and declined with higher sea conditions. ‘Observer’ was also selected as an explanatory variable in the MR model, and suggested that Observer pair 1, positioned in the front of the aircraft, had more detections than Observer pair 2. One member of Observer pair 2 was less experienced, which may have augmented the effect of observer as an explanatory variable in the covariate model.

The detection function for the image sightings (CDS) was found to be independent of the perpendicular distance (Figure 3.1), which is why the strip census technique was applied. This was as expected, as the resolution throughout the frame was of sufficient quality to adequately distinguish individual narwhal and image analysts had ample time to analyze each image in detail. Koski *et al.* (2013) also reported uniform detection of cetaceans throughout the frame of the oblique imagery collected. The detection probability of smaller marine mammals (*i.e.*, pinnipeds), on the contrary, rapidly decreased as distance from the track line increased (Koski *et al.* 2013). This was attributed to lower resolution at the outer edge of the images, which limited the ability to confidently differentiate smaller animals, such as pinnipeds, from debris, dirty ice, waves, *etc.* For this reason, a CDS model should be applied to estimate pinniped population abundance when similar on-water camera resolution is used, instead of a strip census which is appropriate for medium-size and large cetaceans. As detection functions of marine mammal species in aerial surveys depend on various factors (*e.g.*, altitude, camera resolution, species size, detectability below the surface, and environmental conditions, *etc.*), it seems good practice to first attempt to fit a distance model to the data. Based on the obtained detection function, it can then be decided whether to use the distance model or a strip census.

Reduced detection near the trackline

Both the observer and image detection function showed a reduced number of detections near the trackline and highest number of detections around 150 m from the trackline. Various possible explanations were considered for this observation; (i) movement of animals away from the trackline in response to the approaching plane. However, animals below the surface ahead of the aircraft cannot hear the aircraft until it is almost overhead (Richardson *et al.* 1995). Therefore, only animals that are far ahead of the aircraft and at the surface would both hear and have time to move to the side. However, the surface and dive behavior from the satellite tags indicate that surfacing times are not typically long enough for the animals that hear the aircraft to still be at the surface when the aircraft passes over them. Additionally, given the speed that narwhals swim (~2 m/s) and the speed of the aircraft (47 m/s), animals could not be moving away from the trackline in response to the aircraft. (ii) pilots swaying to the sides of sightings on the trackline to provide observers with a better opportunity to observe narwhals. The GPS recordings of the transects were analyzed, which confirmed that pilots stayed on course during the entirety of the survey. (iii) lack of observational effort on the trackline. Reduced sighting effort at the trackline can result in reduced detection probability at $g(0)$. Use of bubble windows enables observers to observe on

the trackline and even on the other side of it. The photographs provided an auditable data set, which confirmed that there were fewer narwhals present closer to the trackline, so this effect was not due to lack of observation effort on the trackline. We concluded that the reduced detection probability at the trackline and the observed peak in detection probability around 150 m is a real and random effect, possibly explained by the limited number of sightings. For this reason, left truncation was not considered in the MRDS, which would also have affected the comparison with the strip census results. To further explore the detection function anomalies, additional sighting data (240 sightings) from three similar surveys conducted in 2012 were combined with the 2014 sighting data. This increase in observations led to less prominent issues with the lack of the shoulder at $g(0)$ and the increased detection around 150 m in the detection function but didn't resolve them altogether. Therefore, these results are not included in this analysis.

Comparison of image and observer sightings

There were considerable differences in the data collection, processing, and analysis methods (*i.e.*, MRDS *vs.* strip census) applied to the observer and image data sets. The available detection range for sightings was also significantly different, with image sightings restricted to a 515 m swath and observers covering a perpendicular view greater than 2,000 m. Image analysts had significantly relaxed time constraints to detect and identify wildlife in imagery compared to aerial observers and real-time visual observations. Detection of narwhals in the Melville Bay aerial image data set was therefore less dependent on factors like distance from the track line, group size, Beaufort, time to next observation, *etc.*, compared to real-time observations. Despite these differences, the narwhal population abundance estimates derived from both platforms were not significantly different.

Differences in group size and perpendicular distance estimation were observed. Aerial observers and image analysts used slightly different definitions for group size. This was done unintentionally as both teams needed to operate independently, and this difference was discovered upon completion of the analysis. However, this difference did not explain the observed difference in group size. As image analysts used a maximum distance of five body lengths to define a group (*vs.* three used by the observers), this difference in definition could potentially have explained larger group sizes for image sightings, but the opposite effect was observed. The data in Table 2 suggest that the observers combined animals into larger groups than the image analysts when encounter rates were high. This likely occurred because of the clustered distribution of narwhals during this survey. With limited time for recording data on multiple close sightings, aerial observers appear to have combined small groups into fewer, larger-sized groups. The smaller number of groups with larger mean group sizes recorded by the observers here, however, resulted in a fairly similar number of observed individuals within 500 m of the track line by both observers and analysts. It might be expected that the number of individuals seen by analysts would be higher than the number seen by the observers within the 500 m swath covered by the images, as observers are expected to miss a fraction of sightings with increasing distance from the trackline. The number of individuals detected by analyst was indeed somewhat higher (~7%) compared

to that of the observers, but this difference was not significant. The significant difference in mean group size calculated for image and aerial observers' sightings was not reported in the baleen whale analysis conducted by Koski *et al.* (2013). Compared to the typically solitary baleen whales, narwhals can occur in larger pods of 10-20 individuals. Therefore, they may be harder to count during real-time observation. Imprecise group size estimates are not uncommon in the presence of numerous simultaneous sightings, and observers tend to underestimate the size of large groups (Norton-Griffiths 1974, Scott *et al.* 1985, Mathews 1995, Lowry 1999, Stewart *et al.* 2013). The tendency to underestimate group size has been observed to increase with group size (Gerrodette *et al.* 2018), although this effect was observed in group sizes (>25 individuals/group) exceeding the ones observed during this survey. Observer performance tends to become degraded at high encounter rates in general, and can affect accuracy of measurement of beam time, declination and species identity as well (Pike and Doniol-Valcroze 2015). Above a certain encounter rate threshold Pike and Doniol-Valcroze (2015) suggest use of a strip survey mode instead of a MRDS, or a combination of visual and photographic data.

Observers had relatively more time to scan the area ahead of the plane for presence of narwhal, compared to analysts that used the images. The application of a different correction factor for availability bias for observers and image data was therefore of importance to avoid overestimation in the observer data set, and to improve the accuracy of the comparison between aerial observer and image-based results. The different adjustment for time in view between aerial observers *vs.* images therefore needs to be taken into consideration when comparing observers *vs.* image-based results. The availability correction factor of 0.22 was based on dive behavior observed in two females in the months August and September and was based on tagging data obtained in Melville Bay in 2007. As female narwhals display different diving behavior compared to males (Heide-Jørgensen *et al.* 2003), and diving behavior of only a limited number of individuals (2) was used in quantifying the correction factor, it's questionable to what extent this availability correction factor is representative for the entire Melville Bay population. The availability correction factor can have a substantial influence on the corrected density and population estimate, and this uncertainty must be considered when reviewing the corrected abundance estimate. However, the primary objective of this study was the comparison of corrected abundance estimates using two platforms of observation, in which both use the same correction factor. For the purpose of this study, the use of this availability factor was therefore considered acceptable.

Koski *et al.* (2013) did not observe major differences in the numbers of cetacean sightings from both platforms either. Koski *et al.* (2013) concluded that high-definition digital images and image review provide similar results to real-time aerial visual observations for monitoring distribution and abundance of large cetaceans in a common swath, but stated that additional data were required to confirm the results obtained with their small sample size. The finding that the abundance estimate of narwhals in the Melville Bay did not differ significantly between a strip census and MRDS models based on sighting and aerial observer data, respectively, support this conclusion, and provide further evidence that aerial image analysis can be a feasible alternative to

aerial observations for cetacean population estimation.

MRDS using matched image and aerial observer sightings

An attempt was also made to develop a second Mark Recapture Distance Sampling model using the image analysts as Observer 1, and the aerial observers as Observer 2. Image sightings were matched to aerial observer sightings based on time, distance, group size, and group composition, and matched sightings were included in this analysis. Different models were tested, with the inclusion of various covariates and a truncation distance of 500 m. The χ^2 goodness of fit test showed significant inaccuracies, including unrealistic abundance and confidence estimates. This was likely due to the small number of high-confidence matches between the two data sets although the total number of animals was almost the same from the two methods. With more precise recording of the time and group size of each sighting by observers in the survey aircraft, a MRDS model based on duplicate sightings between aerial observers and images could provide further insight into observer perception bias and derive more precise abundance estimates.

Advantages and disadvantages of both observation platforms

There are several significant advantages and disadvantages to consider when determining which survey approach best meets the study objectives and requirements. One disadvantage of digital aerial marine mammal photography surveys is that detailed manual analysis of large data sets of digital imagery is time consuming and cost-prohibitive. Additionally, image analysis methods cannot deliver near real-time results necessary for monitoring and mitigation efforts (Koski *et al.* 2013). Marine mammal automated detection software is being developed to alleviate the time burden and high costs associated with image review (*e.g.*, Maire *et al.* 2015), but is not commercially available yet. Similar software exists for object detection in terrestrial environments, where stationary backgrounds and relatively constant object shapes facilitated detection software development. Marine environments, with moving backgrounds and partial visibility of animals at the water surface, have proved to be more challenging (Bajzak and Piatt, 1990, Abd-Elrahman *et al.* 2005, Wichmann *et al.* 2010). Due to the high cost of detailed manual analysis of images, the current cost of traditional aerial surveys with observers is likely equal to, or less expensive than digital aerial surveys, even when using UAS. Marine mammal automated detection software will significantly reduce digital aerial survey costs and image analysis time and could eventually provide real-time marine mammal monitoring capabilities. Thus, development of reliable, cost-effective marine mammal automated detection software will be essential for digital aerial surveys to become an acceptable alternative to traditional observer-based methods.

Another potential disadvantage is that aerial imagery frequently covers a smaller swath than visual observations, which could prove problematic in areas where marine mammal densities are low, or when monitoring to mitigate against potential disturbances to wildlife (Koski *et al.* 2013). Observers are also able to scan farther ahead of the aircraft, covering a greater area than that captured in each image. Animals could potentially dive ahead of the aircraft and reduce the sighting detection availability in the images. Having a larger area of observation to the front and

sides of the aircraft also enables pilots and observers to better adapt to dynamic physical and environmental conditions, such as glacier fronts, mountains, coastal areas and fog. Additionally, there is flexibility to divert from the track line to collect additional off-effort data on a sighting. Pre-programmed UAS are restricted to completing transects in the designated order and are unable to adapt to variable weather or redirect to collect off-effort observations.

Image analysts, however, have significantly relaxed time constraints for the detection and identification of marine mammal sightings, an important advantage over visual observations. Data recorded by analysts are likely more comprehensive and accurate, especially when multiple sightings in close proximity are encountered. Aerial observers can see cetacean sightings for a maximum of approximately 60 s, depending on survey altitude, speed and environmental conditions. As observed in this study, the brief time available for observers to view sightings makes it more difficult to collect accurate group size and perpendicular distance to the track line data, which have implications for the reliability of estimates determined by either CDS or MRDS methods. Additionally, images provide a permanent, auditable record that can be used to quantify biases through independent review and confirmation of species, group size, and perpendicular distance (Koski *et al.* 2013), as was done in this analysis. These data can be shared and re-analyzed and be used to extract other data *e.g.*, presence of other marine mammal species, group structure, and sex and age composition.

Conclusion

The overall objective of these aerial surveys was to gain more insight in the potential impact of seismic hydrocarbon exploration programs on the abundance and distribution of narwhal in Melville Bay. For more detail on this topic we refer to Heide-Jørgensen *et al.* (2013b, 2014).

This is the first published study where marine mammal population abundance estimates derived from a digital image data set and an aerial observation data set were compared. Our results indicate that collection and analysis of high-resolution imagery can be an effective alternative approach to traditional manned aerial surveys for estimating cetacean abundance and provides similar estimates of abundance when appropriate correction factors are applied. Detailed manual analysis of large image data sets is currently cost-prohibitive; however, marine mammal automated detection software will alleviate those cost concerns once available. Digital aerial survey methods associated with UAS have the potential to become the preferred option for marine mammal surveys in coastal areas when comparable results can be delivered near real-time at a competitive cost.

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Appendix 1

Chi-Square good-of-fitness values to test for uniform distribution of detection function over image observers' distance (500 m.) grouped in 100(a), 50(b) and 25(c) m bins.

Null hypothesis: The number of sightings is independent of distance away from the trackline.

Alternative hypothesis: The number of sightings depends on the distance away from the trackline.

Decision: There is no evidence for accepting the alternative hypothesis for all three bin sizes.

Table 1.1: Chi-Square values binned over 100 m.

Cell	Cut Points		Observed values	Expected values	Chi-square values
1	0	100	11	12.4	0.158
2	100	200	20	12.4	4.658
3	200	300	12	12.4	0.013
4	300	400	9	12.4	0.932
5	400	500	10	12.4	0.465

Total Chi-square value = 6.226; Degrees of Freedom = 4.00

Probability of a greater chi-square value, P = 0.18291.

Table 1.2: Chi-Square values binned over 50 m.

Cell	Cut Points		Observed values	Expected values	Chi-square values
1	0	50	4	6.2	0.781
2	50	100	7	6.2	0.103
3	100	150	9	6.2	1.265
4	150	200	11	6.2	3.716
5	200	250	7	6.2	0.103
6	250	300	5	6.2	0.232
7	300	350	5	6.2	0.232
8	350	400	4	6.2	0.781
9	400	450	4	6.2	0.781
10	450	500	6	6.2	0.006

Total Chi-square value = 8.0; Degrees of Freedom = 9.00

Probability of a greater chi-square value, P = 0.534

Table 1.3: Chi-Square values binned over 25 m..

Cell	Cut Points		Observed values	Expected values	Chi-square values
1	0	25	2	3.1	0.390
2	25	50	2	3.1	0.390
3	50	75	4	3.1	0.261
4	75	100	3	3.1	0.003
5	100	125	5	3.1	1.165
6	125	150	4	3.1	0.261
7	150	175	9	3.1	11.229
8	175	200	2	3.1	0.390
9	200	225	3	3.1	0.003
10	225	250	4	3.1	0.261
11	250	275	4	3.1	0.261
12	275	300	1	3.1	1.423
13	300	325	3	3.1	0.003
14	325	350	2	3.1	0.390
15	350	375	1	3.1	1.423
16	375	400	3	3.1	0.003
17	400	425	3	3.1	0.003
18	425	450	1	3.1	1.423
19	450	475	3	3.1	0.003
20	475	500	3	3.1	0.003

Total Chi-square value = 19.3; Degrees of Freedom = 19.00

Probability of a greater chi-square value, $P = 0.438$.

Appendix 2

Results from the CDS models using a uniform detection function, applied on image data using both group (Figure 2.1) and individuals (Figure 2.2) as the main unit for sightings. The results of these analyses are provided in table 2.1.

Figure 2.1: CDS model with uniform detection function using groups as main unit for sightings.

Figure 2.2: CDS model with uniform detection function using individuals as the main unit for sightings.

Table 2.1: Results of the conventional distance sampling models using a uniform distribution with both groups and individuals as the sighting unit.

Sighting unit	Uncorrected density of whales (whales/km ²)	Uncorrected abundance of whales	Corrected density of whales (whales/km ²)	Abundance of whales corrected for availability bias	Lower confidence interval limit	Upper confidence interval limit
Group	0.037 (0.60)	548 (0.60)	0.168 (0.61)	2489 (0.61)	772	8025
Individual	0.037 (0.57)	554.0 (0.57)	0.169 (0.58)	2520.0 (0.58)	818	7761

Appendix 3

AIC values after fitting explanatory variables to the DS and MR models. The final model chosen, Model 1, is given in bold and 'ΔAIC' indicates the difference between the chosen model and the specified model. HN indicates a half-normal form and HR indicates a hazard-rate form for the DS model. The explanatory variables are perpendicular distance (D), group size (S), group size as a factor with three classes (1, 2–5 and ≥6 narwhals) (S₃), Beaufort (BF), side of airplane (SP), observer pair (O) and time to next observation ≤10 sec (T).

Model	DS model	MR model	No. of parameters	AIC	ΔAIC
1	HN: D + BF	D + O + S₃	5	1330.91	0
2	HN: D + BF	D + O + S	5	1332.81	1.90
3	HN: D + BF + S ₃	D + O + T	6	1333.10	2.19
4	HN: D + BF	D + O	4	1333.50	2.59
5	HN: D + BF + S ₃	D + O	5	1335.08	4.17
6	HR: D + BF	D + O + S ₃	5	1336.97	6.06
7	HN: D + BF + S ₃	D + S ₃	5	1343.66	12.74
8	HN: D + BF + S ₃	D + S ₃ + T	6	1344.63	13.73
9	HN: D + BF	D	3	1344.66	13.75
10	HN: D + BF	D	3	1344.66	13.75
11	HN: D + BF + S ₃	D + T	5	1345.84	14.93
12	HN: D + BF + S ₃	D	4	1346.24	15.33
13	HN: D + BF + T	D	4	1346.62	15.71
14	HN: D	D + O	3	1353.66	22.75
15	HN: D	D + S ₃ + SP	4	1360.79	29.88
16	HN: D	D + SD	3	1361.23	30.32
17	HN: D	D + S ₃	3	1362.23	31.32
18	HN: D	D + S ₃ + T	4	1363.21	32.30
19	HN: D	D + S ₃	3	1364.04	33.13
20	HN: D	D + S	3	1364.13	33.22
21	HN: D	D + T	3	1364.42	33.51
22	HN: D	D	2	1364.82	33.91
23	HN: D + S	D	3	1366.40	35.48
24	HN: D + T	D	3	1366.52	35.61
25	HN: D + SP	D	3	1366.56	35.64
26	HN: D + S ₃	D	3	1366.72	35.81

Chapter 4

Site-fidelity and spatial movements of western North Pacific gray whales on their summer range off Sakhalin, Russia

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Abstract

The Western North-Pacific (WNP) gray whale feeding grounds are off the northeastern coast of Sakhalin Island, Russia and are comprised of a nearshore and offshore component that can be distinguished by both depth and location. Spatial movements of gray whales within their foraging grounds were examined based on 13 years of opportunistic vessel and shore-based photo-identification surveys. Site fidelity was assessed by examining annual return and resighting rates. Lagged Identification Rates (LIR) analyses were conducted to estimate the residency and transitional movement patterns within the two components of their feeding grounds. In total 243 individuals were identified from 2002-2014, among these were 94 calves. The annual return rate over the period 2002-2014 was 72%, excluding 35 calves only seen one year. Approximately 20% of the individuals identified from 2002-2010 were seen every year after their initial sighting (including eight individuals that returned for 13 consecutive years). The majority (239) of the WNP whales were observed in the nearshore area while only half (122) were found in the deeper offshore area. Within a foraging season, there was a significantly higher probability of gray whales moving from the nearshore to the offshore area. No mother-calf pairs, calves or yearlings were observed in the offshore area, which was increasingly used by mature animals. The annual return rates, and population growth rates that are primarily a result of calf production with little evidence of immigration, suggest that this population is demographically self-contained and that both the nearshore and offshore Sakhalin feeding grounds are critically important areas for their summer annual foraging activities. The nearshore habitat is also important for mother-calf pairs, younger individuals, and recently weaned calves. Nearshore feeding could also be energetically less costly compared to foraging in the deeper offshore habitat and provide more protection from predators, such as killer whales.

Keywords: gray whale, *Eschrichtius robustus*, Sea of Okhotsk, habitat, feeding grounds, conservation, distribution, movements, site fidelity, lagged identification rates, residency, photo-identification.

Introduction

The Eastern (ENP) and Western North Pacific (WNP) gray whales (*Eschrichtius robustus*) are the only known extant populations of this species. The North Pacific populations were significantly depleted during early- to mid-20th century commercial whaling, while the Atlantic gray whales were hunted to extinction a few hundred years earlier (Henderson 1984, Weller *et al.* 2002, Reeves *et al.* 2010). The WNP whale population was presumed extinct by 1966 (Bowen 1974), but small numbers of gray whales were sighted in the late 1960s and 1970s within the Sea of Okhotsk, South China Sea and the Sea of Japan (Berzin 1974, Brownell and Chun 1977, Maminov and Blokhin 2004). Meanwhile, the ENP gray whale population recovered to close to 21,000 individuals from 1985 onwards (Punt and Wade 2010, Laake *et al.* 2012, Durban *et al.* 2013), with indications that this population may have reached carrying capacity (Coyle *et al.* 2007). The WNP population is recovering at a much slower pace. Pre-exploitation abundance of this population was estimated to be between 1,500-10,000, with 1,000-1,500 individuals remaining in the population in 1910 after commercial exploitation had started (Berzin 1974, Berzin and Vladimirov 1981, Yablokov and Bogoslovskaya 1984). In 2015, the non-calf WNP population numbered ca. 174-186 individuals (Cooke *et al.* 2015). Due to the low population size, the WNP population is listed as endangered in the Red Data Book of the Russian Federation (Anonymous 2001). The IUCN red list status of the WNP population is currently endangered and was updated from critically endangered in 2018 (Reilly *et al.* 2000, IUCN 2012, Cooke 2018).

The main known WNP summer feeding areas are situated in the Sea of Okhotsk (Reeves *et al.* 2008). WNP gray whales have been sighted during the summer off northeast Sakhalin in two main feeding areas: (1) the nearshore waters where whales predominantly feed in shallow waters (<20 m depth) (Weller *et al.* 1999) and (2) the offshore waters where whales feed in deeper water depths (35-60 m) (Maminov and Yakovlev 2002, Meier *et al.* 2007, Yakovlev *et al.* 2009, Fadeev 2011, Tyurneva *et al.* 2012, Vladimirov *et al.* 2012, Demchenko *et al.* 2016). Based on whaling catch data, it was assumed that WNP whales winter at the southern end of the Korean peninsula (Andrews and Schulte 1914). Other historic records suggests these wintering grounds may be as far south as the Yellow Sea, East China Sea and South China Sea (Weller *et al.* 2002). Satellite-tags deployed on WNP individuals (Mate *et al.* 2011, Mate *et al.* 2015) and genetic and photo-ID comparisons between ENP and WNP individuals (Lang *et al.* 2010, Lang *et al.* 2011, Urbán *et al.* 2012, Weller *et al.* 2012, Urbán *et al.* 2013) demonstrated that at least a portion of the WNP whales migrated to Baja California. This indicated some degree of spatial overlap between the two populations, as ENP whales typically migrate from breeding grounds near Baja California to summer foraging areas in the Bering and Chukchi Seas (Jones *et al.* 1984, Moore *et al.* 2000, Swartz *et al.* 2006, Heide-Jørgensen *et al.* 2012). However, genetic studies have consistently found significant differentiation, with some limited genetic exchange occurring (LeDuc *et al.* 2002, Swartz *et al.* 2006, Lang *et al.* 2010, Lang *et al.* 2011, Meschersky *et al.* 2015, DeWoody *et al.* 2017, Brüniche-Olsen *et al.* 2018, Bruniche-Olsen *et al.* 2018). One key difference between the WNP feeding grounds off Sakhalin versus those used by ENP

gray whales, is the spatial area of these feeding grounds. With approximately 600 and 700 km² for the nearshore and offshore feeding areas, respectively, the feeding grounds used by WNP whales (Gailey *et al.* 2020) are drastically smaller in comparison to those used by ENP whales. A tagging study on 23 individuals in the Pacific Coast Feeding Group (PCFG), a subset of ENP whales who do not migrate to the Bering, Chukchi or Beaufort seas to feed, showed individual feeding-area home ranges (90% isopleth) and core areas (50% isopleth) of 3,107 km² ($\pm 4,140$) and 840 km² ($\pm 1,159$), respectively (Lagerquist *et al.* 2019). Home ranges covered most of the near-shore waters from Northern California to Icy Bay, Alaska. Core areas showed a similar range and overlapped for multiple whales in some areas so the total area available for foraging by PCFG whales was significantly larger than the mean individual core area. Similar results were also found for tagged ENP gray whales off Chukotka, Russia, that had a mean core area of 2,087 km² (Heide-Jørgensen *et al.* 2012). The relatively small spatial scale of the WNP whale feeding grounds can make these whales more susceptible to environmental perturbations, such as seasonal ice cover duration (Gailey *et al.* 2020), or anthropogenic disturbance (Yazvenko *et al.* 2007, Bröker *et al.* 2015), as there are no other known feeding areas in the area. As capital breeders, gray whales primarily rely on the acquisition of food resources during their summer feeding season to sustain them through their migration and breeding/calving season (Moore *et al.* 2003, Villegas-Amtmann *et al.* 2015, Villegas-Amtmann *et al.* 2017), with estimated individual gray whale consumption of about 409 kg of benthic prey per day, or ~61 tons during the 5-month feeding period along Chukotka, Russia (Nerini 1984). As bottom-feeding specialists, gray whales feed on benthic and epi-benthic organisms and ingest their food by suction (Ray and Schevill 1974, Nerini 1984, Weller *et al.* 2002). In the nearshore feeding area off Sakhalin, the benthic community is predominately comprised of amphipods (primarily *Monoporeia affinis*), isopods, bivalves, cumaceans, epibenthic crustaceans and sand lance (*Ammodytes hexapterus*) with amphipods presumably being preferential prey for gray whales due to their high caloric content, dense populations and high biomass (Bogoslovskaya *et al.* 1981, Nerini 1984, Highsmith and Coyle 1992). While the nearshore area functions as habitat for smaller/shorter lived amphipods, the offshore feeding area contains dense aggregations of Ampelisca amphipods *Ampelisca eschrichtii* which are much larger and longer lived. Based on stomach content analyses in most other parts of the world these have been identified to be the primary prey for gray whales (Yablokov and Bogoslovskaya 1984, Nerini 1984, Bluhm *et al.* 2007, Coyle *et al.* 2007, Fadeev 2011, Fadeev 2013, Demchenko *et al.* 2016). Annual prey resource studies off Sakhalin found that biomass of amphipods in the nearshore feeding area ranged from higher biomass at shallower depths (93.0 g/m² at 10-15m depths in 2012) to lower biomass in deeper waters (19.9 g/m² at 21-25m in 2012) (Fadeev 2013). In comparison, the mean amphipod biomass in the deeper offshore feeding area (338.2 g/m²) was consistently higher (Fadeev 2013, Demchenko *et al.* 2016). These differences in biomass between the nearshore and offshore feeding areas could be one explanatory factor for some of the observed spatial movement patterns of the WNP population within their foraging grounds (Vladimirov *et al.* 2012, Fadeev 2013, Demchenko *et al.* 2016).

Gray whales are known to display maternally directed site fidelity, which is also observed

in other baleen whales like Humpback whales (*Megaptera novaeangliae*) (Frasier *et al.* 2011). For example, humpback whales follow seasonal migration cycles between high-latitude feeding grounds and low-latitude breeding regions as well (Witteveen and Wynne 2017). Photo-identification studies of humpback whales conducted in the North Pacific and North Atlantic indicated strong site fidelity to feeding areas with high rates of resightings in the same feeding area, and very limited interchange between different feeding areas (Calambokidis *et al.* 2001, International Whaling 2002, Witteveen and Wynne 2017). In the North Pacific this was even the case when feeding areas were in relatively close proximity (<100km) (Witteveen and Wynne 2017), which appeared different from animals in the North Atlantic that make longer daily feeding trips (>100km) (Heide-Jørgensen and Laidre 2007). Gray whales, however, tend to display more focused foraging efforts on a relatively smaller spatial scale with higher coastal affinity (Heide-Jørgensen *et al.* 2001, Heide-Jørgensen *et al.* 2001, Heide-Jørgensen *et al.* 2003, Zerbini *et al.* 2006, Heide-Jørgensen and Laidre 2007, Dalla Rosa *et al.* 2008, Heide-Jørgensen *et al.* 2012), compared to some other species of baleen whales. This may be explained by presence of sufficient prey availability without the need to make long or rapid movement to other areas. (Epi) benthic feeding baleen whales, such as gray whales, but also bowheads whales, are thought to encounter more predictable, but spatially restricted prey concentrations (Laidre *et al.* 2007), than other pelagic fish or krill feeding baleen whales (Laidre *et al.* 2010, Heide-Jørgensen *et al.* 2012). Spatial movement patterns between the two feeding areas off Sakhalin, as well as site fidelity to these areas, are currently not well defined.

In this study, we quantified the WNP gray whale annual site fidelity and residence and examined differences in their utilization of the two components of their feeding grounds off Sakhalin based on a long-term (13-year) photo-identification dataset. Annual return and resighting rates were used as metrics of site fidelity. Residency, defined as the time spent by an animal in a specific geographical area (Wells 1991, Hartman *et al.* 2015), has not been previously determined for WNP gray whales on their feeding grounds. Lagged Identification Rates were used to assess mean residence time on their foraging grounds off Sakhalin as well as within and between the nearshore and offshore feeding areas of their feeding habitat.

Materials and methods

Study area

Annual opportunistic photo-identification surveys of gray whales were conducted in the waters off northeast Sakhalin Island from 2002-2014. The survey areas covered the known nearshore and offshore feeding areas. The nearshore area was approximately 120 km along the shore adjacent to the Piltun and Chayvo lagoons (52.3° - 53.3°N), approximately up to the 20 m contour (~5-10 km from shore, with peak densities between 500 and 2000 m (Muir *et al.* 2016)), with the mouth of the Piltun lagoon located towards the middle. Sightings made within this area were considered nearshore, but also included a limited number of sightings beyond 10 km from shore. The offshore feeding area was mostly south of Chayvo lagoon and approximately 30-40 km from

the coast, with depths of 40–50 m (Fig 1). Sightings between 51.8° and 52.4° N and 143.4° and 144.0° E were classified as offshore. Substrates in the nearshore areas include silty sands with more sandy muds in the offshore area (Blanchard *et al.* 2019). Both feeding areas have amongst the highest primary and secondary productivity in the Sea of Okhotsk (Demchenko *et al.* 2016).

Figure 1: Photo-identification study areas off Sakhalin Island, Russia.

Locations of gray whale sightings in the study area are designated as brown dots. Top right inset shows a regional view of the northeast Sakhalin Island.

Photo-identification surveys

During the period 2002-2014, opportunistic photo-identification effort in the nearshore and offshore areas off NE Sakhalin was conducted from either an inflatable boat (4.8 m) or a larger research vessel. No predetermined systematic survey tracks were followed. Surveys were executed to maximize both spatial coverage as well as encountering and photographically identifying as many gray whales as possible. Marine mammal observers on the research vessel scanned the feeding areas for the presence of gray whales. Upon sighting gray whales an inflatable boat was deployed from the larger research vessel to photographically capture the sighted whales. Animals sighted near the larger research vessel were also photographically captured if conditions allowed. However, this platform was not used to actively approach individuals or groups of gray whales. Additionally, opportunistic, shore-based, photo-identification efforts were implemented from 2004 to 2010 from various observation stations with height ranging from 5 to 30 m. Although maximum observation distance was 10 - 40 km from shore, the maximum distance for identifying individuals was limited to 1 - 3 km, depending on atmospheric conditions, due to limitations of capturing animals with photographic equipment. In 2014 vehicle-based surveys were conducted from the beach during which animals were observed close to shore. In 2014, photo-ID research effort in the nearshore area was expanded to include an additional inflatable boat that was launched from within the Piltun lagoon.

Every observation of a gray whale group was recorded if one or more individuals from that group were photographed, with a sighting being defined as the capture of a single individual. There could be several sightings per survey. A group was defined as either a single animal, or multiple gray whales swimming in proximity to each other (within 10 body lengths) with coordinated behavior relative to other individuals. The inflatable boat team consisted of a boat driver, data recorder, video camera operator, and camera photographer. Whales were slowly approached from the side, with a no-approach zone of 100 m. Individuals were then photographed to capture identifiable features that included the head, fluke, and sides of their body. Priority was given to the right dorsal flank, followed by the left dorsal flank, ventral and dorsal aspects of the fluke. The date, time, camera frame numbers for each individual whale, group size, geographic information (e.g. distance to the whale(s), observer location (via GPS), and environmental parameters such as Beaufort sea state and air temperature were recorded by both vessel- and shore-based photo-identification teams. Vessel-based teams recorded water depth and water temperature as well. A range of cameras were used (Canon (7D), Nikon (D1X, D2X, DF100, DF700)). Vessel-based teams used 70-400 and fixed 300 mm lenses, while the shore-based teams used lenses with extended range from 70-800 mm with up to 2x extenders.

Individual-matching methodology

The field methodology for the photo-identification surveys and matching procedures followed Hammond *et al.* (Hammond *et al.* 1990) with modifications specially aimed at gray whales (Weller *et al.* 1999, Calambokidis *et al.* 2002, Tyurneva *et al.* 2010). Distinctive marks on sides and flukes of gray whales were used to identify individual animals (Hammond *et al.* 1990). The

primary feature for identifying individuals was body pigmentation, whereby scars and barnacle patches could provide additional matching confirmation (Tyurneva *et al.* 2010). The left, right and fluke identifiable aspects of the individual were recognized based on following criteria: (1) the whale was photographed as a solitary individual; (2) photographic series of both sides of the whale with the same fluke were obtained during one sighting; (3) the height, spacing, and ratio of the distinctive knuckles in the ridge on the caudal peduncle were considered as a final check. Identifications and right to left matches were verified by at least two independent matching specialists. Only excellent and good quality photographs were used for matching individuals and right to left matching to avoid false negatives, unless individuals were highly distinctive on images of poorer quality (Friday *et al.* 2000).

Calves usually arrive on the foraging grounds accompanied by their mothers. During the course of their feeding season calves are weaned from their mothers. The weaning commonly occurs from August to mid-September. Criteria for identification of calves and presumed mothers were used that are described in Yakovlev and Tyurneva (Yakovlev and Tyurneva 2013) and included morphological and behavioural features distinctive to calves such as presence of vibrissae, separation distance, as well as the number of sightings with a candidate mother. New individuals were categorized as either calves, i.e. animals meeting the criteria for recently born individuals, or non-calves, i.e. individuals entering the Sakhalin population from elsewhere or individuals that were missed as a calf.

After finalization of the matching process, the highest quality sighting images in terms of clarity, contrast, content and angle (Friday *et al.* 2000), were stored in the photo-identification database software ‘Discovery’ (Karczmarski and Gailey 2013), together with environmental conditions, sighting location, and other sighting information.

Data analyses

Because animals were sighted from multiple observation platforms (i.e. inflatable boat, research vessel, shore-based platforms), effort was determined by using the cumulative number of all sightings made over the season. Differences in nearshore and offshore area usage was assessed by comparing the number of individuals observed in these areas each year, after standardizing the number of seasonal sightings in both areas, using a Chi-squared goodness-of-fit test. For the period 2003-2014 more sightings were made in the nearshore area. Therefore, the number of sightings made in the offshore area was assessed for each year, and consequently the same number of sightings was randomly sampled with replacement from the total pool of nearshore sightings for that same year. The number of unique individuals in this random sample of sightings was then determined. In 2002, more annual sightings were made in the offshore area. The same number of sightings made in the nearshore area in 2002 was therefore randomly sampled with replacement from the total pool of offshore area sightings made in that year. The total number of unique individuals was consequently assessed from that sample of sightings. Discovery curves, i.e. the cumulative number of unique individuals as a function of survey effort, expressed by the cumulative number of sightings, were generated for new individuals, new individuals that were

not calves, and new individuals that were calves.

Site fidelity can be defined as the tendency of an animal to remain in an area over an extended period or to return to an area previously occupied (White and Garrott 1990). This area-restricted space use behavior has important consequences for many ecological processes (Börger *et al.* 2008) and can be estimated by using the repeated presence of individual whales in a feeding areas over time (Witteveen and Wynne 2017). On a population level, site fidelity can also reflect the annual return rate (Witteveen and Wynne 2017). Site fidelity to the Sakhalin feeding grounds was inferred from two different statistics. The first used metric was the annual return rate, which is defined as the number of individuals re-sighted each year after the observation of the total number of individuals for the first time in a given year. The second metric was the annual re-sighting rate, which is defined as the number of individuals sighted in the current year that were identified in previous years, divided by the total number of animals sighted that year (Witteveen and Wynne 2017).

Mean residency times were defined as the time spent by an animal in a specific geographical area (Wells 1991, Hartman *et al.* 2015). Residency times in the study area were estimated by using the Lagged Identification Rate (LIR) (Whitehead 2001, Whitehead 2009). LIR ($R(\tau)$) is defined as the probability of identifying a random individual in an area at time ($t = 0$), and re-sighting that same individual again after a variable lag time (τ) ($t = 0 + \tau$) (Whitehead 2001). $R(\tau)$ is the probability that an individual in a study area at time 0 is also in at after a lag time of τ ($P(\tau)$), divided by the number of individuals (N) in the study area:

$$R(\tau) = P(\tau)/N$$

For any lag time (τ), $R(\tau)$ can be estimated from the proportions of the total pairs of identification τ time units apart ($g(\tau)$), which are of the same individual ($m(\tau)$):

$$\hat{R}(\tau) = m(\tau)/g(\tau)$$

where

$$m(\tau) = \sum_{i,j} \{m_{ij} | \tau_{ij} = \tau\}$$

and

$$g(\tau) = \sum_{i,j} \{n_i \times n_j | \tau_{ij} = \tau\}$$

In these formulas, i, j are used to denote a set of individual identifications collected at a particular time and location, m_{ij} are the number of individuals identified in both set i and set j , τ_{ij} is the time lag between identification sets i and j , and n_i and n_j are the number of individuals identified in i th and j th set, respectively.

LIR plotted over time provides insight in the use of a study area by individuals as the LIR remains constant if a population is closed and identifications are independent. In this case, the LIR is the inverse of the population size. The LIR can decrease with increasing time lag due to emigration and mortality. Non-zero LIR levels indicates that some individuals remain resident

or that emigrated individuals re-immigrate into the study area (Whitehead 2001). Changes in the LIR over the study period were modeled for both all individuals, as well as for animals first seen as a calf, using maximum likelihood methods in the program SOCPROG 2.8 for the period 2002-2014 (Whitehead 2009). Lagged identification times were binned in time lags of increasing duration, and the LIR was calculated for each bin. Consequently, SOCPROG fits models of lagged identification rates using maximum likelihood and binomial loss by applying the full data set, not simply the estimated lagged identification rates (Whitehead 2009). A set of 8 models populated with preset parameters (S1 table 1) was applied to test for closed and open population models, including various combinations of emigration, reimmigration and mortality, and was used to test the empirical dataset (Whitehead 2009). These models were of the exponential form with up to three parameters for processes such as emigration/mortality, mean residency times, mean time out of study area etc. (S1 table 1). The quasi-Akaike information criterion (QAIC) was used to evaluate each model's goodness of fit and account for over-dispersion of data (Whitehead 2007).

LIR were also used to examine the transitional probabilities of movement between the offshore and nearshore area, and to estimate the distribution ratio of the Sakhalin population over these two feeding grounds. Four models, also populated with preset parameters, were used to test the migration rates and mean residence periods between the nearshore and offshore feeding areas (S1 table 1). Both the entire study area and between feeding areas were assessed for the duration of one feeding season as well as for the overall observation period (2002-2014). Transitional probabilities of movement between the offshore and nearshore area using LIR were also established for animals that were first seen as a calf only. The quasi-Akaike information criterion (QAIC) was used to evaluate each model fit and account for over-dispersion of data (Whitehead 2007). In all the selected models, the 95% confidence interval was estimated by bootstrapping from 100 replicates (Buckland and Garthwaite 1991).

Ethics statement

Due to the non-invasive techniques employed in this study, no permits were required for the field observations of gray whales of Sakhalin. Animals were approached in line with the IWC general principles for whale watching. Protocols and methodology for field observations were reviewed by the Western Gray Whale Advisory Panel (WGWAP), established by the International Union for the Conservation of Nature (IUCN), on an annual basis.

Results

Photo-identification efforts were concentrated in the nearshore area, including the nearshore waters off Chayvo lagoon in the south, with additional dedicated survey effort in the offshore area (Table 1). Total survey effort in both feeding areas was not equal with more survey effort in the nearshore area since more animals were initially observed there. The nearshore survey effort was mostly focused around the lagoon mouth due to the consistent presence of large number of

individuals, but surveys were also conducted in the northern and southern parts of the nearshore feeding area (Fig 1) as substantial inter-annual differences in distribution were observed.

The number of individual whales (and calves) identified each year depended on the number of whales in the area, location, and timing and duration of photo ID effort. There was variation in the annual survey dates and duration (Table 1).

Table 1: Summary of photo-identification survey periods, effort, and number of KOGW whales identified for each year off Sakhalin.

Year	Survey Dates	No. of teams	No. of obs. days	Total no. of sightings	No. of Ind.	Resighted ind.	New Ind.	Calves	New non-calf	Total in Catalog
2002	14Sep-15Oct	1/0/0	13	77	49	0	49	0*	49*	49
2003	07Aug-19Sep	1/0/0	26	177	86	38	48	10	38	97
2004	31Jul-01Oct	1/1/0	35	265	101	79	22	3	19	119
2005	13Jul-01Oct	1/1/0	48	502	117	100	17	4	13	136
2006	01Jul-09Oct	1/1/0	51	518	122	110	12	5	7	148
2007	23Jun-05Oct	1/1/0	74	851	127	113	14	10	4	162
2008	01Jul-03Oct	1/1/0	44	317	102	97	5	5	0	167
2009	05Jul-23Sep	1/1/0	42	429	122	111	11	8	3	178
2010	06Jun-27Sep	1/1/0	55	482	121	112	9	7	2	187
2011	19Aug-05Oct	1/0/0	27	351	123	105	18	15	3	205
2012	13Aug-5Oct	1/0/0	33	371	144	130	14	9	5	219
2013	10Jul-11Oct	1/0/0	12	204	121	112	9	6	3	228
2014	26Jul-03Oct	1/2/1	49	696	138	123	15	12	3	243
Total			509	5240	1473		243	94	149	

No. of teams = number of teams per platform (no. of vessel-inflatable boat-based teams / no. of shore-based teams / no. of shore-based inflatable boat teams); No. of obs. days = days with survey effort; 'Total no. of sightings' = number of individuals observed, includes multiple sightings per individual; 'No. of Ind.' = number of unique individuals; 'Resighted Ind.' = individuals that were observed in previous years; 'New. Ind.' = number of individuals observed off Sakhalin for the first time; * = no calves were identified in 2002.

A total number of 243 individual gray whale utilized the feeding grounds off Sakhalin at some point during the period 2002-2014. The total number of individuals was comprised of 94 calves and 149 non-calves (Table 1). A total of 25 reproductive females were seen on the Sakhalin feeding grounds. The first reproductive female was identified around 10 years of age, as a calf seen in 2004 returned with her own calf in 2014. The discovery curve demonstrated that in the first few years of the study, the number of new non-calf whales encountered decreased rapidly and the discovery curve started to plateau after the first 400 sightings, equivalent to approximately the first 3 years of the study (2002-2004) (Fig 2 and 3). In fact, 119 out of the 149 (80%) new non-calf individuals observed in 2002 - 2014 were photographically captured within the first 4 years of survey effort (Fig 2). After these initial 4 years of photo-identification efforts, only 30 new non-calf individuals were observed in a span of 9 years (2006-2014). Thus, the majority of

the newly identified individuals on the Sakhalin foraging grounds after 2005 were largely a result of calf production (72.0%) as opposed to new non-calf individuals (28.0%).

Figure 2: A discovery curve representing the total number of new individuals, number of new non-calves and new calves identified as function of the total cumulative number of identifications made from 2002-2014 in the Sakhalin feeding grounds. No distinction was made between calves and non-calves during the first year of the study (2002).

Sightings within the nearshore and offshore feeding areas

Survey effort in the nearshore and offshore feeding areas was variable with more effort in the nearshore area in 2003–2014 (Table 2). This was due to both an increased amount of vessel-based effort in the nearshore area, as well as shore-based photo-identification efforts.

Table 2: Summary of photo-identification effort within the Sakhalin feeding areas.

Year	Nearshore area			Offshore area		
	No. of surveys	No. of observation days with sightings	Total sightings	No. of surveys	No. of observation days with sightings	Total sightings
2002	8	5	17	17	8	60
2003	14	13	111	21	13	66
2004	24	31	258	3	4	7
2005	54	43	494	2	5	8
2006	22	43	458	4	8	60
2007	47	58	644	8	16	207
2008	22	38	218	8	6	99
2009	28	38	381	3	4	48
2010	22	48	458	5	7	24
2011	20	21	335	--	6	16
2012	20	18	203	14	15	168
2013	15	10	116	5	2	88
2014	28	44	573	10	5	123
Total	324	410	4266	100	99	974

‘No. of surveys’ relates to dedicated inflatable boat-based surveys only, and does not include shore-based surveys or sightings by the large opportunistic vessel. ‘No. of observation days with sightings’ includes days with one or more dedicated surveys as well as days with large opportunistic vessel and/or shore-based sightings. -- = no effort data available.

Nearly all the identified Sakhalin whales (239 out of 243) were observed in the nearshore area at some point during the 13 years of our study. A total of 122 individuals were identified in the offshore area and 118 individuals were seen in both feeding areas. Four individuals were observed only in the offshore area. These four individuals were sighted once and were never seen again in subsequent years. A total of 121 individuals were seen only in the nearshore area and never observed in the offshore area, of which 67 whales (including 44 calves) were seen only once. This included 15 whales (12 calves) that were first seen in our last year of observations (2014).

The total number of sightings, annual number of observed individuals and total number of unique observed individuals were significantly higher in the nearshore area than in the offshore area ($\chi^2 = 2068.2$, $p < 0.001$; $\chi^2 = 231.1$, $p < 0.001$; $\chi^2 = 37.9$, $p < 0.001$, respectively). Survey effort in the nearshore was 3–4 times more compared to the offshore area (Table 2). To correct for

survey effort, the minimum number of sightings in a year in either the nearshore or the offshore area was used for both regions. This standardization of the number of sightings resulted in a total of 931 sightings of individuals in both the offshore and nearshore areas across all years (Table 3). The sum of the total number of individuals identified every year in these 931 sightings was not significantly different between the nearshore and offshore area (540 vs. 512; $\chi^2 = 0.75$, $p < 0.38$), suggesting that sampling heterogeneity was similar in both survey areas. After the correction for effort, the total number of unique individuals in the nearshore and offshore areas was found to be different (200 vs 119; $\chi^2 = 20.6$, $p < 0.001$). This indicates that the nearshore area was used by a larger number of individuals compared to the offshore area, and the difference was not due to an increase amount of effort within the nearshore area.

Table 3: Uncorrected number of sightings, individuals and cumulative number of unique individuals in the nearshore and offshore area, as well as the number of individuals and cumulative number of individuals in the nearshore and offshore area after standardizing for the number of sightings in both areas.

	Uncorrected						Corrected					
	Nearshore			Offshore			Nearshore			Offshore		
	Total sightings	No. ind	Cum. Ind	Total sightings	No. ind	Cum. Ind	Total sightings	No. ind	Cum. Ind	No. ind	Cum. Ind	
2002	17	14	14	60	37	37	17	14	14	14	14	
2003	111	67	74	66	33	51	66	50	58	33	41	
2004	258	100	115	7	6	54	7	7	61	6	45	
2005	494	116	134	8	7	55	8	8	65	7	46	
2006	458	111	146	60	33	65	60	26	78	33	58	
2007	644	107	159	207	68	84	207	113	94	68	81	
2008	218	67	164	99	61	89	99	48	120	61	86	
2009	381	102	175	48	39	92	48	36	129	39	89	
2010	458	116	184	24	21	96	24	19	139	21	93	
2011	335	115	202	16	13	97	16	15	143	13	94	
2012	203	95	217	168	74	106	168	88	173	74	103	
2013	116	68	224	88	67	114	88	57	185	67	111	
2014	573	83	239	123	76	122	123	59	200	76	119	
N	4266	1161		974	535		931	540		512		

‘Total sightings’ = total number of individuals seen during the year - includes multiple sightings of a single individual, ‘No. ind.’ = number of unique individuals seen during the year, ‘Cum. Ind.’ = cumulative number of individuals seen during the survey period.

Site fidelity and residency times

Site fidelity to the Sakhalin feeding ground was found to be relatively high. For example, 10 of the 49 whales (20.4%) seen in Sakhalin in 2002 were sighted every year. Of these 49 whales, 38 (77.6%) were seen during 10 or more years out of the 13 years of photo-ID effort. Out of the 187 animals that could have been observed 5 years or more (i.e. first observed in period 2002-2010), 19.7% (n=37) returned to either study area every year after the year of first sighting.

The mean annual return rates for the study period indicated that of all new individuals seen in a given year, on average over half of those new individuals (64.9%) were seen each year thereafter (Table 4a). In the first two years of survey effort (2002-2003), the mean annual return rates were higher (77.3%) compared to other years (Table 4a). This may be explained by a larger proportion of newly identified non-calf animals vs. calves. A relatively high number of observed calves were sighted only once and not again (35 excluding calves seen in 2014). Excluding those 35 calves seen only once resulted in higher mean annual return rates, i.e. 72.2% vs 64.9% (Table 4b)

The annual resighting rate, i.e. the proportion of individuals sighted during a year that were seen in previous years, was high as well, and leveled off after the first three years of observation (Fig 4). After these first three years the mean rate of annual return was on average 90%, meaning that approximately 9 out of 10 animals sighted during a year have been seen in previous years.

Table 4: Annual return rates of WNP gray whales defined by the total number of unique individuals identified/year and the number of animals resighted in subsequent years.

(a) Year	N	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Mean (n)	Mean (%)
2002	49	38	42	44	46	43	40	42	39	30	39	27	36	38.8	79.3
2003	48	-	37	39	39	40	35	39	34	34	37	33	30	36.1	75.2
2004	22		-	17	14	13	12	13	13	8	13	12	12	12.7	57.7
2005	17			-	11	9	5	8	10	10	11	9	8	9.0	52.9
2006	12				-	8	4	5	4	5	7	3	6	5.3	43.8
2007	14					-	1	3	3	3	2	2	1	2.1	15.3
2008	5						-	1	1	1	1	1	0	0.8	16.7
2009	11							-	8	8	7	5	8	7.2	65.5
2010	9								-	6	6	6	5	5.8	63.9
2011	18									-	7	7	6	6.7	37.0
2012	14										-	7	7	7.0	50.0
2013	9											-	3	3.0	33.3
2014	15												-	n/a	n/a
243														64.9	

Table 4: Continued

(b) Year	N	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Mean (n)	Mean (%)
2002	49	38	42	44	46	43	40	42	39	30	39	27	36	38.8	79.3
2003	46	-	37	39	39	40	35	39	34	34	37	33	30	36.1	78.5
2004	21		-	17	14	13	12	13	13	8	13	12	12	12.7	60.5
2005	16			-	11	9	5	8	10	10	11	9	8	9.0	56.3
2006	9				-	8	4	5	4	5	7	3	6	5.3	58.3
2007	5					-	1	3	3	3	2	2	1	2.1	42.9
2008	1						-	1	1	1	1	1	1	1.0	100.0
2009	9							-	7	8	7	5	8	7.0	77.8
2010	9								-	6	6	6	5	5.8	63.9
2011	10									-	7	7	6	6.7	60.6
2012	12										-	7	7	7.0	58.3
2013	6											-	3	3.0	50.0
2014	15												-	n/a	n/a
208														72.2	

(a) = Including 35 calves that were seen one year and not in following years. (b) = excluding 35 calves that were seen one year and not in following years. 'Year' = original sighting year, 'N' = number of new individuals sighted in original sighting year, '2003-2014' = resighting years.

Area usage

Total area

The average LIR over a season dropped abruptly within the first few days and subsequently decreased gradually over the course of a season, with a small increase after 70 days (Fig. 4 top). Lagged identification rates did not reach zero over the course of a season suggesting that the period of observations did not cover the entire feeding season. The usual start of observations occurred after the first whales arrived on the feeding grounds and stopped before all animals departed for their wintering grounds. For these reasons the maximum residency times could not be assessed. LIR rates over the survey period 2002-2014 saw a decrease within the first year, followed by a subtle lag period of 13 year (Fig 4 bottom). Based on the QAIC criteria, models 7 (emigration + reimmigration) and 8 (emigration + reimmigration + mortality) were selected for the annual ($\chi^2 = 93.4$, d.f. = 69, $p < 0.05$) and multi-year LIR ($\chi^2 = 1529.8$, d.f. = 1320, $p < 0.01$), respectively. The selected model for the annual and multi-year LIR was 92 and 91 individuals, respectively, present on the Sakhalin feeding grounds at any given time during the feeding season. The mean number of days of whales remaining on the Sakhalin feeding grounds compared to outside of the Sakhalin feeding grounds during the feeding season was estimated to be 72.0 and 41.9 days for the annual season and 64.3 and 32.6 days for the multi-year data set (S2 Table 1). These figures may have been an underestimation as no data were collected early during the feeding season (mid-May - June) and later in the season (October - December). Multi-year LIR for animals first seen as calves are provided in S3 Fig. 1.

Figure 3: (a) The annual number of new and resighted gray whales and (b) the annual resighting rate (resighted individuals / total number of sighted individuals (new + resight)).

Figure 4: LIR for a single season (top) and for the total study duration (2002-2014) (bottom). The green circles provide the LIR of different lagged time bins.

Seasonal movement between nearshore and offshore area

LIR between the ‘nearshore to nearshore’ area (i.e. the likelihood that a random individual first seen in the nearshore area was sighted there again) decreased over the course of a field season but did not reach zero, indicating that some, but not all, animals left this area (Fig 5 top-left). Over this same period, a continuous increase in LIR values between the ‘nearshore into offshore’ area was observed, suggesting a movement of individuals from the nearshore to the offshore area over the season (Fig 5 top-right). The likelihood of seeing individuals in the offshore area first and consequently in the nearshore area was low but increased for the first 10 days suggesting some movement back and forth between both feeding areas (Fig 5 bottom-left). There was a decrease in LIR values in the ‘offshore to offshore’ model after 10-20 days, after which the LIR remained

constant between 20 – 40 days (Fig 5 bottom-right). These LIR values were high in comparison to the ‘offshore to nearshore’ LIR values, suggesting that more animals stayed in the offshore area instead of moving to the nearshore area. Furthermore, ‘offshore to nearshore’ LIR values were low in comparison to ‘nearshore to offshore’ values which is indicative of more animals moving from the nearshore to the offshore area, instead of the other way around.

The maximum lag for the offshore to offshore area for which LIR values could be obtained was 40 days, which was noticeably less than the maximum lag of the nearshore to nearshore area (>70 days). This was likely due to reduced survey effort in the offshore area, with less time between the first and last surveys over a season. Details of the chosen models were included in S2 Table 2. The selected models fit did have anomalies in the estimated number of animals and mean residence times. For that reason, these values were not considered.

Figure 5: LIR and selected models within and between the offshore and nearshore area within a season. Red stars and green circles are the LIR of different lagged time bins.

Multi-annual movement between nearshore and offshore area

Lagged identification rates between the nearshore to the offshore area increased over the course of the first season and then gradually increased from year two up to a lag period of 7-8 years (Fig 6 top-right). This means that once animals start migrating to the offshore area during a season, most of them continued to do so consistently in following seasons. Of specific interest was the steep increase in LIR after 12 years, with LIR values twice as high compared to after one year. These results suggest that especially mature animals (>12 years) utilized the offshore feeding area more frequently and younger animals less frequently or not at all, as is the case with calves and

yearlings. (In fact, only 11 of the 94 calves (12%) observed in the nearshore area during 2003-2014 were also seen on the offshore feeding area during later years. The average period between the first sighting of a calf in the nearshore area and the first sighting of that individual in the offshore area for these 11 individuals was about 5 seasons (4.8 ± 1.85). Of the 122 individual Sakhalin whales never observed in the offshore area, 83 (68%) were first seen as calves, 19 (16%) were non-calves that were seen only once on the nearshore area and not again, 6 (5%) were reproductive females which were known to prudentially utilize the nearshore area and 14 (11%) did not fit in these three categories. This indicated a demographical difference in area usage with younger animals more frequently utilizing the nearshore area, and increased use of the offshore area by older animals.

As previously mentioned, there was limited movement between the offshore to the nearshore area within the first year of observation in the offshore area (Fig 6 bottom-left). However, increased LIR values for lags of 2-8 years indicated that animals seen in the offshore area moved consistently to the nearshore area in following years (Fig 6 bottom-left). After 8-12 year, LIR values decreased suggesting reduced use of the nearshore area with increased maturity. This finding corresponds with the above-mentioned high 'nearshore to offshore' LIR values for mature animals. LIR values for the 'offshore to offshore' area for lags larger than a year (Fig 6 bottom-right) appeared more constant and decreased less in comparison with LIR values for 'nearshore to nearshore' for similar lags (Fig 6 top left), suggesting higher site fidelity to the offshore area. The model output was not further considered as the model fits were either poor, or had anomalous estimates for animals present on the feeding grounds and residency times. LIR trends within and between the nearshore and offshore areas for the period 2002-2014, based on animals that were first seen as calves (S3 Fig 2 top-right), had somewhat similar trends as those for based on all individuals (Fig 6). The LIR values for 'nearshore area to offshore area' for calves only showed a more profound increase compared to that based on all individuals. One other difference was that there was no negative or positive trend observed in the 'offshore to offshore area' LIR based on animals first seen as calf, as was the case in that based on all individuals (S3 Fig 2 bottom-right). This suggests that once the few young animals move the offshore area, they consistently return to this area in following years.

Figure 6: LIR within and between offshore and nearshore area over the duration of the study period (2002-2014). Red stars and green circles are the LIR of different lagged time bins.

Discussion

Photo-identification is an important methodological technique that provides a means to understand individual spatiotemporal movement patterns of gray whales. The gray whale is a suitable species for photo identification studies as individuals are born with unique and persistent pigmentation patterns and display consistent scarring and ectoparasites patterns (Rice and Wolman 1971, Darling 1984, Bradford *et al.* 2011). Although scarring and parasite patterns can change over the years, individuals can typically be identified with certainty as these patterns change slowly and most animals are seen consistently over the year(s), providing a chronological photo record. Natural pigmentation, ectoparasites and scarring can also be used to reliably distinguish calves from yearlings, even in the absence of their mothers (Bradford *et al.* 2011).

Whales feeding on the Sakhalin foraging grounds consistently returned annually during this 13-year study period. The discovery curve plateaued after the initial three years of photo-identification effort with further increases of new individuals being primarily a result of reproduction. This is an indication that the WNP gray whale population is a closed population with little to no immigration at least on their foraging grounds. The 31 new non-calf whales observed in the period 2006-2014 could either be new individuals that immigrated from the ENP population or calves of the WNP population that this photo-identification study was unable to capture as a calf, which is known to occur at times. Similarly, Weller *et al.* (Weller *et al.* 1999) found that the discovery curve plateaued after 4 years of survey effort of gray whales off Sakhalin. The spatial area of our surveys covered a larger area which included the entire nearshore and offshore areas and demonstrates that there was little immigration of new adults to the Sakhalin feeding grounds. This result is also consistent with population models conducted by Cooke *et al.*

(Cooke *et al.* 2013, Cooke *et al.* 2015) who concluded that the Sakhalin gray whale population is demographically self-contained with growth rates being exclusively a product of calf production and little immigration into the population. One presumably female whale with a calf was known to be 10 years old since this whale was sighted as a calf. This observation is in line with other observations of gray whale reaching age of sexual maturation between the ages of 5 and 12 (Rice 1990, Bradford *et al.* 2010).

The formation of “feeding groups” that show high site fidelity is not uncommon among gray whales. For example, a small group of ENP gray whales (the Pacific Coast Feeding Group) has consistently been observed to feed between the Californian coast and the Alaskan peninsula (Calambokidis *et al.* 2010, Scordino *et al.* 2011). Another example is by Heide-Jørgensen *et al.*, who observed high fidelity in satellite-tracked ENP gray whales to relatively small-scale summering feeding grounds off Chukotka, Russia, as well. High site fidelity to feeding areas is not always observed in baleen whales, with daily feeding trips exceeding 100 km/day in some species such as blue whales (*Balaenoptera musculus*), fin whales (*Balaenoptera physalus*) and minke whales (*Balaenoptera acutorostrata*) (Heide-Jørgensen *et al.* 2001, Heide-Jørgensen *et al.* 2001, Heide-Jørgensen *et al.* 2003), but can occur in some other baleen whales species, such as humpbacks and bowhead whales (Laidre *et al.* 2007, Witteveen *et al.* 2011, Heide-Jørgensen *et al.* 2012). Gray whales are unique among baleen whale as they are true (epi)benthic foragers, although bowhead whales can target dense prey concentrations near or on the seabed as well (Laidre *et al.* 2007). (Epi)benthic foragers are more likely to show high site fidelity to specific feeding grounds where there are predictable, high density, but spatially restricted, prey concentrations (Heide-Jørgensen *et al.* 2012). Given the large energy needs of these large whales, they likely have evolved to exploit their prey in regions with high density aggregations (Laidre *et al.* 2007).

Area Usage

A closer examination of the area usage within the Sakhalin feeding grounds within and between years indicated a higher area usage of the nearshore area versus the offshore area, with more individuals making use of the nearshore area in comparison to the offshore area. Three possible explanations, which are further described below, include: 1) biased survey effort (i.e., higher survey effort in the nearshore area), 2) availability of more accessible (i.e. shallower) food resources in the nearshore area, and 3) demographical differences in area use. Since about 76% of our survey effort occurred in the nearshore area, the high degree of area usage here compared to the offshore area could have been a result of effort bias, but after correcting for survey effort, more individuals were still seen in the nearshore area. Although more individuals were seen in the nearshore area, lagged identification rates suggested a higher site fidelity to the offshore area, especially when animals start to mature.

Gray whales are known to be opportunistic feeders, taking advantage of changes in food availability (Nerini 1984, Moore *et al.* 2003, Moore *et al.* 2007). Bluhm *et al.* (Bluhm *et al.* 2007) suggested that gray whale area usage is linked to high prey density, which has been seen in

other baleen whale species as well (Curtice *et al.* 2015). This was thought to be a more important explanatory factor for gray whale density than the taxonomic composition of the available prey. The prey resources in the nearshore area are mainly comprised of smaller amphipods (*Monoporeia affinis*) distributed in aggregated patches that vary significantly in biomass concentration from year to year (Fadeev 2011), but include other prey species as well (Blanchard *et al.* 2019). In contrast, the offshore area is comprised of a high concentration of ampeliscid amphipods (*Ampelisca eschrichtii*), with a mean biomass of 338.2 gr/m² (Fadeev 2013, Demchenko *et al.* 2016). The offshore area is deeper (40-60m) and therefore potentially more energetically demanding than the nearshore area (<20 m), but also likely to be more energetically rewarding due to this high biomass of prey availability.

A third possible explanation is that mother-calf pairs, and young animals, prefer the shallow near shore waters over the offshore area. In the 13 years of offshore feeding area surveys no calves, mother-calf pairs or yearlings have been observed in the offshore area, and only 12% of calves (11) seen between 2003-2014 were observed in the offshore area. Based on shore-based behavioral studies in the nearshore feeding area, it is known that mother-calf pairs and weaned calves in the nearshore feeding area have significantly longer respiration intervals and shorter dive times compared to other individuals (any individual excluding mothers, calves and yearlings) (Sychenko 2011). Furthermore, even within the nearshore feeding area there is spatial age-class segregation as observed by significant differences in the mean distance to shore between mother/calf pairs (0.55 km), weaned calves (0.81 km) and other individuals (1.30 km) (Sychenko 2011). The relatively shallow depths in the near shore feeding area compared to the offshore area, is likely to make it easier for a mother-calf pair to access prey resources. Nearshore affinity of gray whale mother-calves on breeding and feeding grounds, as well as during migration, has been observed in several studies (Herzing and Mate 1984, Würsig *et al.* 2000, Perryman *et al.* 2002, Sychenko 2011). Another possible reason for avoidance of the offshore area by calves, yearling and young animals is predator avoidance behavior. Transient killer whales have been observed each feeding season to traverse through their foraging grounds off northeastern Sakhalin. A high percentage of killer whale tooth scars were found on WNP gray whales compared to similar estimates for other baleen whale species (Weller *et al.* 1999, Weller *et al.* 2018). Little interaction between the two species has been observed off Sakhalin, however, but killer whale attacks, both of calves and adults, are common in certain areas off California, Alaska and Chutoka, Russia (Weller *et al.* 2018). For example, the risk of predation of gray whales by killer whales was studied over a 10-year period along Chukotka by Melnikov and Zagrebin (Melnikov and Zagrebin 2005) who found that two-thirds of approximately 100 reported killer whale attacks on marine mammals were on gray whales. The shallow nearshore area may provide more shelter or avoid detection due to the noisy surf region compared to the offshore area, although the specific mechanism is not well understood. Gray whales off California are observed to 'hide' from killer whales behind rocks or in kelp beds (Poole 1984). It has been hypothesized that kelp could offer a physical and an acoustic screen for protection through possible interference with echolocation used by killer whales either by the gas-filled pneumatocysts, or canopy and surf noise (Poole 1984). The

nearshore feeding area lacks rock formations and kelp beds, but presence of surf noise could make acoustic detection by killer whales more difficult. We therefore hypothesize that younger animals make more use of the nearshore feeding season because of a combination of easier prey availability and reduced risk of killer whale attacks. With increasing age, mature animals may be better able to access the deeper and abundant prey of the offshore area needed to sustain their increased energy requirements (Villegas-Amtmann *et al.* 2017, Schwarz *et al.* 2020).

WNP population size

In the early 1970s, the WNP gray whale population was thought to be extinct as a result of over-exploitation from commercial whaling, until a few gray whales were seen in the Sea of Okhotsk (Berzin 1974, Brownell and Chun 1977, Maminov and Blokhin 2004). Since then there has been an intensive effort to study the population size, health, and origin of these gray whales (Weller *et al.* 1999, Bradford *et al.* 2008, Tyurneva *et al.* 2010, Cooke *et al.* 2013). Mark-recapture estimates of WNP gray whales population size yielded a non-calf estimate (with 90% Bayesian confidence intervals) of 122 (CI = 113 - 131) individuals in 2006 (Cooke *et al.* 2006), 121 (112 - 130) non-calf individuals in 2007 (Cooke JG 2007), 130 (120 - 142) non-calf individuals in 2008 (Cooke *et al.* 2008), 140 (± 6) non-calf individuals in 2012 (Cooke *et al.* 2013) and 174 (158-191) to 186 (171-203) non-calf individuals in 2015 (Cooke *et al.* 2015) (depending on whether individuals last seen as calves were considered to have died or merely left). In our study a total of 82 calves were identified in the period 2003-2013 of which 35 animals (43%) were not resighted after the first year of observation. It is not known whether these calves died or just did not return to the Sakhalin feeding ground. Considering the high site fidelity expressed by Sakhalin gray whales and low survival rates observed during calves' first year of life (Cooke 2017, Gailey *et al.* 2020), it is more likely these animals died. Low calf survival rates for baleen whale calves is not uncommon and observed in, for example, ENP gray whales (Swartz and Jones 1983, Punt and Wade 2010) and humpback whales as well (Gabriele *et al.* 2001). In the total study period (2002 -2014) a total of 243 individuals were observed, with identification of a total of 184 individuals (or 172 excluding 12 calves seen in 2014) in the last three years of this period (2012-2014). This number is within the Cooke *et al.* (Cooke *et al.* 2015) estimated range.

Site fidelity and movement patterns

LIR values decreased during the first season of observation and reduced gradually over the following survey years due to emigration and/or mortality, indicating that animals return consistently to the Sakhalin feeding area. Some animals in the nearshore area were there only for part of the feeding season, with gradual migration to the offshore area over the remainder of the season, probably driven by availability of food resources. Other animals in the nearshore area, mostly calves or young animals, but also 6 out of 25 reproductive females, did not move to the offshore area. Individuals in the offshore area displayed higher within-season site fidelity

in comparison to the nearshore feeding area, with only limited movement to the nearshore area. However, animals seen in the offshore area were consistently seen in the nearshore area in future years. They seemed to follow an annual cycle of first arriving on the nearshore feeding area with movement to the offshore area during the latter part of the feeding season. Use of the nearshore area decreases with increasing lagging rates (8-12 years).

The fact that within-season LIR values did not approach zero, and remained fairly constant after the maximum observed within-season lag period of 70-80 days, was indicative of insufficient duration of the survey period to fully capture the migration towards wintering grounds. The nearshore feeding area was typically sea ice-free after June (Gailey *et al.* 2020), although individuals can arrive on the foraging grounds before ice-free conditions (Mate *et al.* 2015, Gailey *et al.* 2020), and photo-identification field seasons mostly started in July. Survey efforts ended around the beginning of October due to adverse weather conditions often prevailing in this period. Migration towards the breeding grounds is characterized by temporal segregation of different age, sex and reproductive classes, with pregnant females migrating first, followed by non-pregnant females, adult males and immatures (Rice and Wolman 1971, Herzog and Mate 1984). Based on individuals that were satellite tagged, onset of migration of at least three non-pregnant individuals started towards the end of November up to mid-December (Mate *et al.* 2015). Whereas some demographic classes may have started migration before then, e.g. pregnant females, these findings confirm that photo-identification efforts did not cover the entire feeding season.

The slow and gradual decrease in multi-year LIR value demonstrates high site-fidelity to the feeding grounds off Sakhalin, i.e. the likelihood of sighting a specific individual after the first year of observation did not decrease much over the 13 years of observation (Fig. 4). The observed small decrease in LIR starting after a lag of one year can be explained by emigration and mortality, as well as the growth in population size, which reduces the likelihood of resighting a specific individual. LIR rates between the nearshore and offshore areas demonstrated a constant exchange between these two feeding areas. As mentioned previously, a gradual increase of nearshore mature individuals moving into the offshore area over a feeding season was detected, which may be explained by reduced prey levels in the shallower feeding ground over the season, warranting feeding in deeper waters with high prey biomass. These results were consistent by the study of Heide-Jørgensen *et al.* (Heide-Jørgensen *et al.* 2012) who also found gray whale affinity to relatively shallow areas (<30m) off Chukotka, Russia, and an increased use of deeper areas (70m) later during the feeding season. Although some mature animals frequent the offshore area in the later part of the feeding season, LIR values indicated that these individuals typically arrive in the nearshore area early during the next feeding season, followed by the move to the offshore area later in the season. The steep increase at nearshore to offshore LIR values at 13 years demonstrates an increased preference of mature animals to the offshore area, which could be related to the higher energetic demands of the larger animals (Schwarz *et al.* 2020), an enhanced ability to feed in deeper waters or a reduced risk of killer whale predation. This type of age class spatial segregation is commonly observed in gray whales, not just during the feeding season but also during migration and on the breeding grounds (Rice and Wolman 1971, Herzog and Mate

1984, Poole 1984, Perryman *et al.* 2002, Heide-Jørgensen *et al.* 2012).

The combination of (i) high site fidelity of WNP gray whales to the nearshore and offshore feeding ground, (2) absence of other known feeding areas in the Sea of Okhotsk, and (3) the relatively small spatial area of the nearshore and offshore feeding areas, makes the WNP population more susceptible to environmental changes and/or anthropogenic disturbance such as fisheries or oil & gas development. Despite these factors this WNP gray whale population has seen an average growth rate of 4.3% between 2005 and 2015 (Cooke *et al.* 2015), but warrants continued focus to ensure this upward trend continues.

Off Sakhalin, a greater understanding of WNP gray whales' utilization, movement and site fidelity within their foraging habitat facilitates the development of new, or adjustment of existing, conservation management efforts of this population (Parra *et al.* 2006). For example, offshore oil and gas activities in the vicinity of the nearshore feeding area have the potential to impact the WNP population and require detailed mitigation strategies (Yazvenko *et al.* 2007, Bröker *et al.* 2015). Lastly, quantification of spatiotemporal movement parameters is also needed to better assess the potential population level consequences of disturbance in specific risk assessment frameworks (Villegas-Amtmann *et al.* 2015, Villegas-Amtmann *et al.* 2017). This is especially the case when bioenergetic models are used that require information on anthropogenic or natural factors affecting energy intake, energetic cost of movement patterns over the available feeding areas and difference in prey availability in these areas (Villegas-Amtmann *et al.* 2015, Villegas-Amtmann *et al.* 2017). In fact, interannual variation in the energy reserves of whales has been detected and correlated with both prey availability and whale fecundity (Bradford *et al.* 2012), as well as with sea spring ice cover (Gailey *et al.* 2020). During years with more sea ice cover or lower prey availability in the nearshore feeding area, animals might make more use of the offshore area to compensate. An enhanced understanding of these processes and movement patterns are therefore relevant for purpose of conservation management.

Conclusions

This long-term photo-identification study identified that most of the WNP gray whale population consistently returned to their summer foraging grounds in the Sea of Okhotsk on an annual basis. WNP gray whales display a high degree of site fidelity to both feeding areas off Sakhalin. More WNP gray whales make use of the nearshore feeding area, in comparison to the offshore area. This is especially the case during the early years of individuals, which may be due in part to more easily accessible food resources and a more protective environment from predators for young animals. There is a consistent seasonal and multi-year movement between the nearshore and the offshore feeding areas. This includes more seasonal movement of mature individuals from the nearshore into the offshore feeding area over the course of a season, and eventually reduced usage of the nearshore feeding area. The long-term nature of our photo-identification dataset, high rate of annual return of individuals to the feeding grounds, and the consistent trend

of observing most “new” individuals as calves (as opposed to adults), along with little evidence of immigration allows us to conclude that the gray whale population returning annually to Sakhalin waters is demographically self-contained. The nearshore and offshore Sakhalin feeding grounds are therefore important areas for summer feeding of young individuals and mothers, and mature animals, respectively.

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Supporting information

S1 Table 1: Models run for Lagged Identification Rates.

Name	Explanation	Equation
<i>With one study area (N is population size in study area):</i>		
1	Closed ($1/a1 = N$)	$a1$
2	Closed ($a1 = N$)	$1/a1$
3	Emigration/mortality ($a1 = \text{emigration rate}$; $1/a2 = N$)	$a2 \cdot \exp(-a1 \cdot td)$
4	Emigration + reimmigration ($a1 = \text{emigration rate}$; $a2/(a2 + a3) = \text{proportion of population in study area at any time}$)	$(1/a1) \cdot \exp(-td/a2)$
5	Emigration/mortality ($a1 = N$; $a2 = \text{Mean residence time}$)	$a2 + a3 \cdot \exp(-a1 \cdot td)$
6	Emigration + reimmigration + mortality	$(1/a1) \cdot ((1/a3) + (1/a2) \cdot \exp(-(1/a3 + 1/a2) \cdot td)) / (1/a3 + 1/a2)$
7	Emigration + reimmigration ($a1 = N$; $a2 = \text{Mean time in study area}$; $a3 = \text{Mean time out of study area}$)	$a3 \cdot \exp(-a1 \cdot td) + a4 \cdot \exp(-a2 \cdot td)$
8	Emigration + mortality + reimmigration ($a1 = N$; $a2 = \text{Mean time in study area}$; $a3 = \text{Mean time out of study area}$; $a4 = \text{Mortality rate}$)	$(\exp(-a4 \cdot td)/a1) \cdot ((1/a3) + (1/a2) \cdot \exp(-(1/a3 + 1/a2) \cdot td)) / (1/a3 + 1/a2)$
<i>With two study areas (N is total population size):</i>		
1	Fully mixed ($1/a1 = N$)	$a1$
2	Fully mixed ($a1 = N$)	$1/a1$
3	Migration—full interchange ($a1 = \text{diffusion rate from area 1 to area 2}$; $a2 = 1/N$)	$a2 \cdot (1 - \exp(-a1 \cdot td))$
4	Migration—full interchange ($a1 = N$; $a2 = \text{Mean residence time in area 1}$)	$(1/a1) \cdot (1 - \exp(-td/a2))$

Models run as preset in SOCPROG 2.7 (Whitehead, 2009). Parameters test for population closure (1 and 2), as well as emigration, reimmigration, and mortality rates (3 to 8). The quasi-Akaike Information Criterion was used for goodness of fit.

S2 Table 1: Selected models for Lagged Identification Rates for the Sakhalin feeding grounds, including no. of selected model, p-value, estimated number of individuals and mean residence times.

	Model selected	P	N	Mean res. time in	Mean res. time out	Mortality
Single season	7	0.027	92.2	72.0	41.9	--
Multiple season	8	0.000	91.5	64.3	32.6	0.16x10 ⁻³

S2 Table 2: Selected models for Lagged Identification Rates between and within nearshore and offshore areas, including no. of selected model, p-value, estimated number of individuals and mean residence times.

	from	to	Model selected	P	N	Mean res. time	Mean res. time in	Mean res. time out
Single season	Nearshore	Nearshore	5	0.77	73.3	118.7	-	-
	Nearshore	Offshore	4	0.44	147.7	32.3	-	-
	Offshore	Offshore	5	0.71	62.3	138.1	-	-
	Offshore	Nearshore	4	0.77	1479.8	2.1	-	-
Multiple season	Nearshore	Nearshore	8	0.07	65.6	-	50.9	38.6
	Nearshore	Offshore	4	<0.0001	158.3	28.7	-	-
	Offshore	Offshore	8	0.99	41.2	-	2.3	2.0
	Offshore	Nearshore	4	<0.0001	324.9	64.9	-	-

S3 Figure 1: LIR for total study area and study duration (2002-2014), based on individuals that were first observed as a calf.

S3 Figure 2: LIR within and between offshore and nearshore area over the duration of the study period (2002-2014), based on individuals that were first observed as a calf.

Chapter 5

Monitoring and impact mitigation during a 4D seismic survey near a population of gray whales off Sakhalin Island, Russia

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Abstract

A 4D seismic survey was conducted in 2010 near the feeding grounds of gray whales off Sakhalin Island, Russia. To minimize disruptions to the whales' feeding activity and enhance understanding of the potential impacts of seismic surveys on gray whales *Eschrichtius robustus*, an extensive monitoring and mitigation plan (MMP) was developed. Typically, mitigation plans involve observers on seismic vessels to monitor for the presence of marine mammals in an exclusion zone so as to prevent physical injury to the animals. Due to the protected status of western gray whales, an additional protection zone based on a behavioural disturbance threshold of exposure of 156 dB re $\mu\text{Pa}^2\text{-s}$ per pulse was applied for whales within their feeding habitat defined by the estimated 95% abundance contour. Real-time radio-transmitting acoustic recorders were deployed along this contour to verify modelled acoustic footprints within the feeding grounds. Shore- and vessel-based observation teams monitored for the presence and activity of whales. A real-time GIS workflow tracking procedure was developed that integrated acoustic and whale positioning data to determine if sound levels at a whales' position within the feeding area exceeded the behavioural threshold, in which case a shut-down of the seismic source was implemented. Additionally, behaviour and distribution surveys were conducted before, during and after the seismic survey to evaluate the effectiveness of the MMP. No large changes in whale movement, respiration, or distribution patterns were observed during the seismic survey. This could be interpreted to mean that the MMP was effective in reducing the sound exposure and behavioural responses of gray whales to seismic sounds.

Keywords: Seismic, mitigation, western gray whale, *Eschrichtius robustus*, Sakhalin, Piltun, Sea of Okhotsk, anthropogenic disturbance .

Introduction

Anthropogenic sound can have physiological and behavioural impacts on marine mammals as well as affect their ability to communicate, navigate and forage (Richardson *et al.* 1995, Nowacek *et al.* 2007, Southall *et al.* 2007). Furthermore, certain anthropogenic sound sources have the ability to cause stress, or, under specific conditions, even injury to the auditory system (Southall *et al.* 2007). Seismic surveys can be an important anthropogenic contributor to the marine soundscape due to the number of surveys conducted and the high source levels involved. The potential physical and behavioural impacts of seismic sound on marine mammals have been the focus of numerous studies (reviewed in Southall *et al.* 2007, Nowacek *et al.* 2007), which have advanced understanding of responses for certain cetacean species (e.g. Malme *et al.* 1986, Malme *et al.* 1988, Finneran *et al.* 2002, Lucke *et al.* 2009, Blackwell *et al.* 2013, Kastelein *et al.* 2013, Schlundt *et al.* 2013). Although the exact impacts of seismic surveys on cetacean auditory systems, behaviour and ultimately population dynamics depend on many factors and are generally not well understood, the need for mitigation measures to prevent adverse effects is broadly accepted. This is particularly true when the sound exposures occur over a prolonged period and/or originate from multiple sources in critical habitat of endangered species.

Sakhalin Energy Investment Company is developing oil and gas reserves from two platforms located in the Piltun-Astokh license area on the northeastern Sakhalin shelf, Russian Federation (Figure 1). One of these platforms is the Molikpaq (hereafter 'PA-A') that began operations in 1999. By 2010, the company needed to characterize changes to the subsurface structure resulting from extraction of hydrocarbons and this required seismic imaging, whereby downward-directed acoustic pulses emitted in the water column are used to probe the sub-bottom layers. These resulting data were considered essential for the efficient positioning of new wells (LGL 2010). The 2010 Piltun-Astokh seismic survey, contracted to DalMorNefteGeofizika (DMNG), provided an accurate replication of a portion of the preproduction dataset that had been acquired in 1997. The two datasets combined enabled the mapping of production-related changes in the hydrocarbon-bearing reservoir beneath the seabed. It was necessary that acquisition¹ conditions and array configuration be identical to the 3D seismic survey conducted in 1997 to allow differential visualization over the fourth dimension of time (hence the terminology, 4D survey). The acquisition area was 170 km², centered around the PA-A platform. As an energy source, two airgun arrays of 2620 in³ were used, configured in a flip-flop (alternate firing) mode. The survey was conducted from 17 June to 2 July 2010.

The 4D seismic survey area was situated directly offshore (between 5 and 15 km) of the Piltun near-shore feeding ground of gray whales (*Eschrichtius robustus*). The 'western' gray whale population is listed as a Critically Endangered subpopulation in the IUCN Red List of

¹ Seismic acquisition is a key component of geophysical hydrocarbon exploration; it involves the generation and recording of seismic data using a source, usually air guns, and different receiver configurations, e.g. a string of hydrophones towed behind a seismic vessel. The source generates acoustic vibrations that travel into the sea bottom, pass through strata with different seismic responses and filtering effects, and return to the surface to be recorded.

Threatened Species (Reilly *et al.* 2008) and as endangered in the Russian Red Book (Anonymous 2001). Recent findings on gray whale migration between the eastern and western North Pacific have led to reviews of stock structure hypotheses, but further studies are required to better understand the genetics and history of what has long been known as the western gray whale (Mate *et al.* 2011, Urban *et al.* 2012, Weller *et al.* 2012, Urban *et al.* 2013, Cooke *et al.* 2013, Bickham *et al.* 2014, IWC 2014). A recent assessment estimated the median non-calf Sakhalin 'population' (i.e. animals regularly found off Sakhalin island) in 2012 to be 140 whales, with a 3.3% mean annual population growth rate (Cooke *et al.* 2013).

The Piltun feeding ground is one of two known feeding grounds off northeastern Sakhalin and it extends over a distance of 110 km between Okha in the north and Chayvo Bay in the south (Figure 1). Most observations of gray whales have been during the ice-free months (June – November) within the 20 m isobath where they feed on the isopods and amphipods that occur at high densities in this area (Fadeev 2011). Apart from the rich benthic prey biomass (average of 35.2 gm⁻² and 18.5 gm⁻² for amphipods and isopods respectively) (Fadeev 2011), the Piltun feeding area is of particular importance to nursing/weaning gray whale calves, probably due at least in part to the relatively sheltered and shallow nature of the area (Sychenko 2011). The location or locations of this population's wintering grounds are not well understood, but the whales are clearly migratory, at least some of them migrate from Sakhalin to low-latitude areas along the Baja California Peninsula, Mexico where early calf rearing and courtship activity occurs (Urban *et al.* 2013), and others possibly to historical wintering grounds in the South China Sea (Weller *et al.* 2002). The whales return to the Piltun feeding area in the period from June to July and remain until November. Gray whales display a high degree of site fidelity with most of the individuals photo-identified off Sakhalin Island being observed there nearly every year (Tyurneva *et al.* 2013). They largely fast for approximately 6-7 months during the breeding and migration period, relying on stored energy acquired during the foraging period at high latitudes. Most individuals are in sub-optimal body condition upon arrival in the northern feeding grounds (Rice and Wolman 1971, Tyurneva *et al.* 2013) but recover their body condition over the course of the feeding season (Weller *et al.* 2001, Bradford *et al.* 2012, Tyurneva *et al.* 2013). One conservation concern is that the effects of disturbance caused by increasing industrial activity in and near the Piltun feeding area could impair the whales' ability to restore their body condition. Poor body condition, whether due to natural or anthropogenic causes, is known to affect growth, survival and reproductive health in other marine mammals (e.g. New *et al.* 2013, 2014).

Apart from the overall loudness of sound generated by the air gun arrays, a main concern associated with seismic sources is that their dominant frequency range (<200 Hz) overlaps with the optimal auditory sensitivity band of baleen whales (Southall *et al.* 2007). Controlled exposure experiments that examined responses of migrating and feeding gray whales to seismic survey sounds in the northern Bering Sea (Malme *et al.* 1986, Malme *et al.* 1988) found that 50% of the whales stopped feeding at received sound pulse levels of 173 dB re 1 µPa rms. Approximately 10% of the animals interrupted feeding at received pulse levels of 163 dB re 1 µPa rms. Despite the application of mitigation criteria based on these thresholds, behavioural responses and changes

in distribution, including changes in swim speed, reorientation rate, distance from shore, blow interval, and dive time were observed in gray whales during a 3D seismic survey off Sakhalin in 2001 (Gailey *et al.* 2007a, Johnson *et al.* 2007, Yazvenko *et al.* 2007). Although localized displacement was observed, the whales remained within the feeding area throughout that survey. The long-term and population-level effects of such localized displacements on the fitness and reproductive success of gray whales are unknown.

Whereas global and national guidelines exist for mitigating the potential impacts of seismic energy on marine mammals (e.g. JNCC 2010, Nowacek *et al.* 2013), no guidelines on seismic mitigation measures are prescribed by environmental regulators within Russia. Various countries have adopted different sets of mitigation and monitoring requirements (summarized in Weir and Dolman 2007). Typically, impacts of seismic activity on marine mammals have been mitigated by defining an exclusion zone around the air gun array at a radius within which physiological damage to the auditory system can occur. Marine Mammal Observers (MMOs) monitor this exclusion zone for the presence of marine mammals as the air guns gradually ramp-up to full-power prior to the start of seismic acquisition. It is assumed that marine mammals move away from the seismic vessel as the generated sound levels gradually increase (Weir and Dolman 2007). These measures, however, only mitigate the risk of physiological damage to animals and do not address behavioural responses, masking, or increased stress levels which can occur at lower sound exposure levels (reviewed in Nowacek *et al.* 2007, Southall *et al.* 2007). The 2010 Piltun-Astokh Marine Mammal Monitoring and Mitigation Plan (MMP) went beyond common mitigation measures by including a real-time monitoring element to mitigate behavioural impacts through the application of an acoustic threshold and criteria for aberrant behaviour, i.e. indicators of stress/avoidance.

The objectives of the MMP for the 2010 Piltun-Astokh 4D survey were two-fold: 1) to prescribe multiple measures aimed at minimizing physical and behavioural effects of seismic acquisition on gray whales and 2) to augment the available data on the effects of seismic sound on gray whale behaviour, abundance, and distribution. In development of the MMP, the following international guidelines and criteria were considered:

- Joint Nature Conservation Committee guidelines for minimizing the risk of injury and disturbance to marine mammals from seismic surveys. Guidelines developed by the United Kingdom and have been applied informally elsewhere in Europe and Africa (JNCC 2010).
- High Energy Seismic Survey Review Process and Interim Operational Guidelines for Marine Surveys Offshore Southern California (HESS 1999).
- United States Minerals Management Service Guidelines on Implementation of Seismic Survey Mitigation Measures and Protected Species Observer Program in the Gulf of Mexico (MMS 2007).
- Guidelines/Recommendations as applied in Australia (Australian Government 2008)
- Southall *et al.* (2007) criteria for injury and behavioural responses for marine mammals.

The mitigation and monitoring strategy used during a 3D seismic survey by Exxon Neftegaz Limited in 2001 (Johnson *et al.* 2007) directly adjacent to the Piltun feeding ground was used as a foundation for further development of the strategy for the 2010 Piltun-Astokh 4D survey. Specialists under contract to Sakhalin Energy Investment Company collaborated with the Western Gray Whale Advisory Panel (WGWAP), an advisory panel of independent scientists convened by the International Union for Conservation of Nature, in a Seismic Survey Task Force (SSTF) to develop the MMP. This was an intense process that took several workshops and meetings beginning with a workshop in June 2007 and with the MMP details finally being agreed in April 2010; the relevant reports can be found at <https://www.iucn.org/wgwap/wgwap/>. A description of the overall process to develop the MMP, generalized to provide a broad approach to minimizing disturbance to wildlife from seismic surveys is given by Nowacek *et al.*, 2013.

This paper summarizes the mitigation and monitoring program designed to minimize the sound exposure impacts of the 2010 Piltun-Astokh seismic survey on gray whales and describes its execution during the seismic survey. From a broader perspective, we provide insights intended to improve management of the acoustic impacts of seismic survey operations on cetaceans in general. Detailed analyses of observations on the behaviour and distribution of the gray whales are summarized in Gailey *et al.* (2014) and Muir *et al.* (2015b, 2016). A detailed overview of the acoustic monitoring conducted during this survey is outlined in Racca *et al.* (2014) and Rutenko *et al.* (2012a).

Figure 1: Overview of the Piltun feeding area showing the estimated gray whale 95% abundance contour based on June-July 2005-2007 shore-based and vessel survey data, 13 distribution stations, three behaviour stations and the two Sakhalin Energy offshore platforms.

Development of the MMP

General overview of the MMP project area and set-up

A primary objective of this MMP was not only to prevent permanent or temporary threshold shifts in gray whale hearing, but also to minimize adverse behavioural responses by gray whales on near-shore feeding grounds. Given the migratory nature of the whales into and out of their summer feeding grounds, we began with the premise that the most effective mitigation measure was to try to conduct the survey as early in the season as possible given the environmental conditions, i.e. before most of the whales arrived on the feeding grounds off Sakhalin Island.

We estimated the Piltun feeding area boundary using data collected by shore-based and vessel surveys from June to July in 2005, 2006 and 2007 (Muir *et al.* 2015a). An acoustic perimeter monitoring line (PML) was defined as a segment of this boundary spanning the length of the seismic survey area, and this line was used in monitoring sound levels at the edge of the feeding grounds (Figure 2). After a thorough review of the available literature, which is limited, we eventually based our acoustic threshold levels on the work of Malme *et al.* (1986), who found that 10% of gray whales in the northern Bering Sea interrupted feeding when exposed to a received sound level of 163 dB $1 \mu\text{Pa}$ rms. We applied an equivalent per-pulse sound exposure level of 156 dB re $\mu\text{Pa}^2\text{-s}$ (henceforth abbreviated to 156 dB SEL) as a behavioural response threshold. The 156 dB SEL threshold was computed from estimation of seismic survey pulse duration at the appropriate propagation range (Racca *et al.* 2015). The use of SEL as the target metric provided much greater stability than rms values in both modelled and measured pulse levels, thus enabling a more reliable comparison between the 2 in the field (Racca *et al.* 2015).

The mitigation plan for the 2001 ENL Odoptu 3D seismic survey had used the same behavioural mitigation threshold albeit expressed in terms of the rms sound pressure metric. This plan used 20 m isobaths as a proxy for the Piltun feeding area boundary and created a 4 km buffer zone, known as 'Area A', seaward of the boundary (Johnson *et al.* 2007). The operating assumption was that acquiring seismic lines within Area A would generate sound levels on the feeding grounds exceeding the behavioural threshold of 163 dB re $1 \mu\text{Pa}$ rms; additional mitigation measures were therefore applied to those lines, such as shutting down when whales were observed in the buffer zone and restricting seismic operations in Area A to daylight hours and periods of good visibility. A 1 km safety or exclusion zone surrounding the seismic vessel was also applied. A shut-down of the seismic source was ordered if gray whales were observed within this area during acquisition to prevent injury to the hearing system.

We developed these concepts to implement behavioural mitigation in our MMP by identifying seismic lines, termed 'A-lines', as those that could ensonify the delineated feeding grounds at sound levels greater than the 156 dB SEL behavioural threshold, and by restricting acquisition of these lines to daylight hours and good visibility conditions. We also used the concept of a 'feeding buffer zone', but, in contrast to the static 'feeding buffer zone' applied in the 2001 Odoptu 3D seismic survey, we allowed this behavioural protection buffer, or 'A-zone', to have a dynamic size and shape that was determined by the seismic line actually being acquired

and by the prevailing propagation conditions. We defined this A-zone for an individual line as the overlap between the 156 dB SEL isopleth generated by the seismic vessel when sailing that line and the estimated boundary of the feeding grounds (Figure 2). The A-zone for an A-line was monitored during acquisition of that line by shore- and vessel-based teams. Mitigation measures specific to A-lines were implemented such as shut-down of the seismic source if gray whales were observed in an A-zone during acquisition. The remaining seismic lines at greater distances from the feeding grounds were called 'B-lines.' Less restrictive mitigation measures were applied to B-lines because it was assumed that their acquisition would not result in exposure of animals in the feeding area to sound levels exceeding 156 dB SEL.

Figure 2: Schematic depicting the survey layout including varying acoustic contours (not accurate representations) depending on line number and propagation conditions in the area. Received acoustic levels at the perimeter monitoring line were monitored continuously via a real-time link with the receiving station located at the southern part of the Piltun lagoon (adapted from Nowacek et al. 2013, used with permission).

Creation of A-zones and designation of A-lines

An acoustic envelope was developed for each seismic line based on acoustic propagation modelling using environmental parameters thought to prevail at the time of the survey (termed default or ‘base’ conditions). The Airgun Array Source Model (MacGillivray 2006) was used to generate the close-range directional acoustic footprint for the specific airgun array configuration to be deployed during the survey. The obtained directional levels served as input to the acoustic propagation model ‘Marine Operations Noise Mode’ (MONM), an extension of the parabolic equation code RAM (Collins *et al.* 1996), to generate long-range sound level contours for several 10s of source points along each seismic survey line. The shoreward envelope (maximum extent) of the individual contours for the 156 dB SEL behavioural threshold, maximized over depth, defined the acoustic envelope for that seismic line.

Each acoustic envelope was projected in a Geographic Information System (GIS) to determine if that line’s 156 dB SEL contour overlapped with the feeding area boundary (Figure 2), thus resulting in an A-zone. This projection was called a ‘base case’. Since the propagation conditions during the survey could be different from the default base case and vary over the survey duration, a library of 156 dB SEL acoustic envelopes corresponding to different propagation regimes and sound level adjustments was generated before the field season for each seismic line. In other words, in addition to the default propagation regime, model scenarios corresponding to low and high sound propagation regimes and level offsets in 1 dB increments, ranging from –5 to +5 dB, were pre-computed and stored. A propagation regime and a sound level offset were jointly referred to as a ‘model case’; a subset of the 33 possible model cases for a single seismic line is shown in Figure 3. Figure 4 shows 3 model cases for the closest shoreward line of the seismic survey and illustrates how the A-zone boundary could be expected to vary according to propagation conditions within the range of feasible cases considered in the modelling. The 12 westernmost lines, out of the total of 35 seismic lines, resulted in A-zones under default conditions and were therefore classified as A-lines.

A-lines were acquired in a south–north direction, and B-lines, in a north–south direction. This was determined by the direction of the line as acquired in 1997, i.e. this was unrelated to the 2010 classification of an A- versus B-line. The relative orientation of the A-lines to the feeding area boundary meant that the seismic vessel’s distance to the feeding area decreased as acquisition progressed. Thus, depending on the propagation conditions, the seismic array might not encompass the feeding grounds with sound levels >156 dB SEL, i.e. result in an A-zone, over the full length of the survey line, but only when the northern part of a line was acquired. We determined from acoustic modelling the most southern location for each line where an A-zone would begin, and applied a 500 m buffer margin southward of this point to define the transition point where the specific mitigation measures designed for A-lines took effect (Figure 4). South of the transition point, less stringent B-line mitigation measures were applied (for precautionary reasons an exception was made for the 3 seismic lines nearest to the feeding grounds, which were always treated as full A-lines). The yellow areas in Figure 2 depict the area covered by the partial A-lines under default propagation conditions. The rationale behind the definition of partial A-lines was

to avoid unnecessary application of the more restrictive mitigation measures associated with the presence of an A-zone, thus facilitating the completion of the survey as early in the season as possible. Once the vessel was past the transition point, A-zone-specific mitigation measures were applied independent of the position of the seismic vessel in relation to an observed gray whale in the A-zone. Animals located in the A-zone, but north or south of the seismic vessel, would not necessarily be exposed to pulse levels >156 dB SEL, as sound levels were highest on the broadside beam of the airgun array (Racca *et al.* 2012b). Their detection would trigger a shut-down nevertheless, making the statically defined A-zone a precautionary mitigation strategy.

Figure 3: Behavioural protection zone boundaries for the most near-shore survey line under standard, low, and high propagation regimes (solid and dashed blue outlines) infilled by finer level adjustments in 1 dB SEL steps (thin red outlines).

Figure 4: Example of three model cases for line 1, i.e. the most near-shore line. Left plate: propagation conditions HIGH, +5 dB offset. Mid plate: propagation conditions BASE, 0dB offset. Right plate: propagation conditions LOW, -5dB offset. The white left X indicates the beginning of the A-zone with corresponding position of the seismic vessel (white right X). The red X includes the 500 m safety margin, i.e. shut-down is required from this point onwards upon observation of whales in the A-zone.

Acoustic monitoring configuration

A 20 km segment of the feeding area boundary adjacent to the seismic survey area was designated as the PML. A network of 9 Telemetered Autonomous Underwater Acoustic Recorders (T-AUARs) was deployed along the PML (Figure 2), with the objective of real-time verification of the accuracy of the acoustic modelling results determining the classification of A- versus B-lines, and the shape of the A-zone for A-lines (Rutenko *et al.* 2012a). The T-AUAR digital acoustic recorders (16 bit, 30 kHz sample rate to internal hard drive) were installed at 2.5 km intervals on the sea floor, with radio telemetry of a subsampled waveform (~4 kHz sample rate) provided via tethered transmitting buoys. Temporary malfunction of a single device was acceptable under the terms of the MMP, but the distance between 2 active T-AUARs had to be no less than 5 km to ensure accurate realtime verification of modelled results over the full length of the PML. Therefore, no seismic acquisition could take place if 2 adjacent T-AUARs malfunctioned until at least 1 unit was put back into operation. The 9 channels of digital data were transmitted via a VHF link to an acoustic receiving station located at the southern tip of Piltun lagoon (Figure 2) (Rutenko *et al.* 2012a). The telemetered data were archived to disk and processed by a front-end computer for spectral characterization, then streamed in 1 min batches over a local network to an independent system for analysis of airgun array pulse levels and ongoing verification of model estimates throughout the acquisition of each seismic line (Racca *et al.* 2012a). Additionally, 3 non-telemetric archival acoustic receivers (AUARs) were deployed within the Piltun feeding area on the 10 m isobath to provide shallow water data for post-operation analysis of the sound field from the seismic survey. In parallel with acoustic monitoring, the coordinates of all vessels operating around the survey area were acquired with an Automatic Identification System (AIS) receiver and displayed on a GIS map for immediate interpretation of the activities and to be logged to disk for future reference.

Model case selection and real-time verification

The onshore acoustic team would begin logging the received pulse levels from the AUARs on a multichannel display when the seismic vessel reached the start of a line. The pulse levels from the first minute of acquisition at the 3 T-AUARs closest to the line starting point were used for the selection of the best model case for that line run. This was done by comparing the average measured pulse levels at the 3 T-AUARs to the predicted levels at the same sites provided by the set of model cases for the active line. The model case that resulted in the smallest residual between the forecast and measured start-of-line levels was selected, which determined the shape and area of the A-zone (Racca *et al.* 2015). The selected model case identifier was broadcast to 3 visual observation teams (2 based at tower platforms on the shoreline and 1 on the observation vessel) who then retrieved the corresponding pre-modelled A-zone boundary from a locally stored GIS database. The appropriate A-zone boundary would appear as a map overlay in the specialized cetacean tracking software systems (Pythagoras; Gailey & Ortega-Ortiz 2002) which processed gray whale observation fixes from theodolites and Whaletrack II (Gailey 2006) which processed estimations from reticle binoculars. Both of these systems produced geo-referenced coordinates of animals overlaid with an A-zone boundary on the same map. This enabled the teams to assess in real-time whether a whale sighting was within or outside the estimated region of the A-zone and react according to the response procedures outlined in the MMP.

The acoustic team used a custom software application to display a real-time chart of the received pulse level traces at all the PML stations as the source vessel progressed along the line. The application screen also allowed a direct comparison between the selected model case and measurement at a given sensor. The active model case was deemed to be in compliance with the MMP directives if the measured pulse level trace remained within a tolerance band of +3 dB from the modelled trace. A violation of this condition would have meant that the current A-zone boundary being used by the visual observation teams was no longer applicable and would have to be updated with another model case.

The 2010 Piltun-Astokh seismic survey MMP: Mitigation

Timing and area

Avoiding or minimizing spatial and/or temporal overlap of anthropogenic activity with marine mammal presence is the most effective means of mitigating the effects of acoustic energy on marine mammals (JNCC 2010). For this reason, the spatial overlap with the feeding area was minimized by reducing the acquisition area of the 2010 survey to <20% of the area surveyed in 1997 (from ~1000 to ~170 km²). This reduction was feasible because the production-related changes that needed to be surveyed occurred only in a subset of the area surveyed in 1997 (LGL 2010). This area reduction also resulted in a substantial decrease in survey duration and cumulative acoustic sound levels.

Limiting factors for acquiring seismic data include (1) the presence of sea ice from December to June, as a totally ice-free sea surface is required for maneuverability of the seismic

vessel and its ~6 km long towed streamers and (2) the generally poor sea states from October to December when severe storms are frequent. The available window to conduct the seismic survey was therefore limited to the period of June through September. The number of gray whales observed on the Piltun feeding grounds is initially low (June to July), with the main influx of animals occurring in August to September (Vladimirov *et al.* 2013) (Figure 5). Starting the survey immediately at the time of ice-free conditions, and completing it prior to the arrival of the majority of the population, was the most important mitigation measure of this MMP. To start the survey as soon as the sea ice allowed, historical ice data were examined to determine average ice-free dates. Additionally, in the weeks prior to the survey, satellite data depicting ice development in the Sea of Okhotsk were monitored on a daily basis to fine-tune the earliest starting date as a basis for mobilizing the seismic and support vessels and the field teams. The scheduled duration of the seismic survey was approximately 3 wk.

Reduction of source array volume

Various options for reducing the effective acoustic footprint of the airgun array were considered in the design of the repeat survey, subject to the requirement that the results of the imaging be sufficiently similar to the original 1997 survey to allow their differential (time-lapse) interpretation. The analysis showed that it would be possible to reduce the total volume of the airguns while preserving the necessary spectral similarity of the acoustic output; as a result, the airgun array size was reduced (from 2840 to 2620 cubic inches).

Figure 5: June–July (left) and August–September (right) average estimated densities based on 2005–2007 data are shown overlaid with the 2010 seismic survey area. The dotted circles provide mean viewing ranges from the three behavioural stations (zero reticle distance at 0 tide height). The blue line represents the PML.

Exclusion zone

The exclusion zone applied around the seismic array, with the radius determined by the 180 dB re 1 μ Pa rms threshold at the broadside maximum, was consistent with the guidelines of the US National Marine Fisheries Service and the High Energy Seismic Survey team (NOAA 1998, HESS 1999). The alternative single-impulse criterion for the onset of physical injury (198 dB re 1 μ Pa²-s SEL) (Southall *et al.* 2007) was considered, but due to the protected status of the whale population, as well as the limited underlying knowledge of hearing frequencies for baleen whales, a precautionary decision was made to apply the 180 dB re 1 μ Pa rms criterion (Nowacek *et al.* 2013). Based on criteria established by the US National Marine Fisheries Service, an exclusion zone with a threshold of 190 dB re 1 μ Pa rms was applied for an endangered population of pinnipeds (the Steller sea lion *Eumetopias jubatus*) known to occur in the area (NMFS 2000). A sound source verification experiment (SSV) was conducted prior to the start of the seismic survey to determine the distance from the seismic array to the 180 and 190 dB re 1 μ Pa thresholds. A precautionary default exclusion zone of 2 km was applied until the results of the SSV experiment were available. A cautionary safety margin of 20% was to be applied if the exclusion zone based on the SSV turned out to be <1.7 km, and the exclusion zone radius was prescribed not to be smaller than 1 km.

Visual monitoring of the exclusion zone from the seismic vessel

Experienced MMOs were placed on all vessels involved in the seismic survey, i.e. the seismic vessel, 2 support vessels and an environmental monitoring vessel. On the seismic vessel 'Pacific Explorer', 2 observers were on duty at any given time 20 min before ramp-up, during ramp-up and during acquisition, to monitor the exclusion zone for the presence of marine mammals. To prevent observer fatigue, shifts were limited to a maximum 2 h continuously on watch with a minimum of 1 h between shifts. The lead MMO on the Pacific Explorer had the authority to request shut-down of the airguns immediately upon observing cetaceans or Steller sea lions to enter the 180 and 190 dB re 1 μ Pa rms exclusion zones, respectively. A precautionary shut-down was also implemented if any of these marine mammals were observed to be on course to enter the exclusion zones.

Behaviour shut-down criteria for gray whales

In addition to the exclusion zones applied to prevent auditory injury, shut-down criteria were implemented for gray whales observed within the identified A-zone and thus potentially exposed to sound levels >156 dB SEL that could trigger behavioural responses. Shut-downs were also implemented when an animal was observed to display aberrant behaviour outside the A-zone. This was defined as a consistently high speed of travel (>10 km h⁻¹), mother–calf pair separation of >5 body lengths, or repeated multiple breaching (i.e. leaping above the sea surface) with correspondingly high speeds of movement away from a potential source of disturbance. When visibility deteriorated to the extent that the A-zone could not be monitored effectively during acquisition of A-lines, a shut-down was ordered. The same applied for the exclusion zone around the seismic vessel if the line had not been scouted in the previous 6 h.

Pre-shooting search

Following Joint Nature Conservation Committee (JNCC) recommendations, MMOs conducted a preshooting survey of the exclusion zone for 20 min prior to the start of ramp-up (JNCC 2010). No ramp-up was initiated if whales were seen in the exclusion zone during this period.

Ramp-up

After any period of seismic source inactivity longer than 20 min, a ramp-up procedure was implemented over the course of at least 20 min. Ramp-up was initiated with the smallest airgun (20 cubic inches) with progressively larger gun combinations being activated at regular intervals, resulting in approximately 6 dB increments. Although broadly, but not universally, accepted as effective, the objective of ramp-up is to prevent animals from being exposed to abrupt increases in sound levels and give them an opportunity to move away from the seismic array prior to fullpower operation. The seismic array was shut down if cetaceans or Steller sea lions were observed in the exclusion zone or were judged likely to enter it during ramp-up.

Line changes

The airgun array was completely shut down during line changes, which took approximately 3 h. In early planning it had been intended to operate the smallest airgun ($\sim 328 \text{ cm}^3$ [20 in³]) during line changes to deter marine mammals away from the seismic vessel (cf. 'ramp-up'). This mitigation measure, however, was not included by the company in the final MMP for various reasons: its effectiveness was considered undemonstrated, it would have introduced additional acoustic energy into the marine environment, and it was considered impractical for technical reasons as line turns were used to depressurize and service the airgun arrays. A pre-shooting search and ramp-up procedure were instead conducted prior to the acquisition of each line.

Monitoring requirements during acquisition

The A-zone was monitored by 2 onshore behaviour teams and a vessel-based team for the presence of gray whales prior to and during acquisition of A-lines. If gray whales were observed within the A-zone prior to the start of a line, seismic acquisition would be delayed by 6 h; that period would be lengthened to 12 h if cow-calf pairs were observed. A-lines were not acquired at night or when insufficient visibility prevented effective monitoring of the entire A-zone. B-lines could be acquired at night or during poor weather conditions, on the condition that the entire line was scouted for the presence of cetaceans during the preceding 6 h (during the survey a maximum of 6 h darkness per 24 h cycle was anticipated). Scanning was conducted by MMOs either from the scout vessel or from the seismic vessel whilst sailing an adjacent line (lines were spaced approximately 300 m apart). The JNCC guidelines recommend the use of Passive Acoustic Monitoring (PAM) whilst shooting at night or in poor visibility (JNCC 2010). The use of PAM was not considered beneficial, however, because gray whale vocalizations have rarely been detected during the course of acoustic monitoring programs conducted on the near-shore feeding grounds since 2002 (Borisov *et al.* 2012).

Independent observer

An observer, designated by the WGWAP, independently reported on the implementation of the monitoring and mitigation measures (Hurley 2010). The observer was stationed on shore to observe monitoring teams and the central command center. Although the observer was only present during the first part of the survey, he concluded that the MMP was implemented successfully and that it appeared efficient in protecting a population of whales from harmful exposure to seismic sound (Hurley 2010).

Table 1: Summary of mitigation and monitoring measures taken during the 2010 Piltun-Ashtokh seismic survey.

Survey conduct	
A-Line Selection and Update	<ul style="list-style-type: none"> Model predictions define the initial survey area for which special A-line mitigation is required. Received levels to be monitored at the feeding area perimeter at all times to ensure that before a predicted A-line is acquired, the acoustic model can be re-calibrated using measured levels. Re-tuning of the model will be undertaken at regular intervals. In the event that the 163 dB rms threshold is unexpectedly exceeded during normal acquisition, operations will immediately be suspended or shifted away from the feeding area until a re-calibration exercise can be undertaken, and the lines re-classified accordingly.
Mitigation and monitoring measures	
Design	<ul style="list-style-type: none"> Survey size optimized. Area < 20% of original 1997 survey. Lines that are predicted to result in levels >163 dB rms within the gray whale feeding area (A-Lines) are to be acquired as early as possible. Gray whale feeding area boundary specific to the timing of the survey.
Timing and duration	<ul style="list-style-type: none"> Survey to commence as early as logistically possible after the start of open-water conditions. Survey duration as short as logistically possible.
Real-Time Acoustic Monitoring	<ul style="list-style-type: none"> Real-time monitoring of acoustic levels using sea-bottom receivers at all times during airgun activity. A minimum of nine monitoring radio telemetry stations positioned at 2500 m intervals along the edge of the feeding area. Never more than 5000 m between active stations. Stations in place and verified to be functioning correctly before acquisition commences. Direct radio link between onshore real-time acoustic monitoring stations and the Senior MMO on seismic vessel.
Archival Acoustic Monitoring	<ul style="list-style-type: none"> Deployment of at least three archival acoustic receivers near the 10 m isobath within the feeding area.
Marine Mammal Observers	<ul style="list-style-type: none"> Experienced MMOs on all involved vessels for survey duration. Minimum of two active MMOs on the seismic vessel at any given time during ramp-up, shooting, and for the 20 min. before start of ramp-up. MMOs limited to maximum 2 hr continuous shift with minimum 1 hr between shifts. Senior MMO on seismic vessel has single point authority for shut-down. All vessels and real-time acoustic monitoring team will have direct radio access to the on-shift Senior MMO. MMO observation platforms will be located at the highest elevation available on each vessel with the maximum viewable range from the bow to 90 degrees port/starboard of the vessel. Monitoring vessel to serve as additional MMO platform for behaviour teams with direct radio link to the Senior MMO on the seismic vessel to activate shut-down when required during the acquisition of an A-Line.

Table 1: Continued

Pre-Shoot Observation and ramp up	<ul style="list-style-type: none"> • Ramp-up required after more than 20 min. of inactive source. • Before start of ramp-up procedures from shut-down, MMOs will be required to conduct a 20-min. pre-shoot observation of the full array exclusion zone. • Ramp-up procedures will be activated over 20 minutes prior to the acquisition of a new line. • Ramp up to occur across a period of time such that a progressively larger gun combination is activated over a 20 min. period (6 dB increments).
Safety Radius	<ul style="list-style-type: none"> • Safety radius for cetaceans determined by direct measurement of the range at which the full airgun array acoustic level drops below 180 dB rms at the broadside maximum, plus a precautionary margin of 20% to be applied if the measured range is less than 1700 m. • Calibration of the safety radius will be required promptly after the commencement of acquisition. • Until calibrated, a safety radius of 2 km for cetaceans will be employed. • The minimum safety radius to be employed after calibration is 1 km. • Safety radius for endangered pinnipeds corresponds to broadband received level of 190 dB rms.
A-Lines	<ul style="list-style-type: none"> • No acquisition in periods of poor visibility or darkness. • No acquisition unless the perimeter monitoring line is within the effective sighting distance of a shore station or an additional vessel. • No acquisition if any gray whales have been observed in the A-zone over the preceding 6 hrs (not implemented when animal was seen to leave the A-zone). • No acquisition if cow-calf gray whale pairs have been observed in the A-zone in the preceding 12 hrs (not implemented when animals were seen to leave the A-zone).
Shut-down	<ul style="list-style-type: none"> • Shut-down to be initiated if a cetacean is observed in the defined exclusion zone for cetaceans. • Shut-down to be initiated if endangered pinniped is observed in the defined exclusion zone for pinnipeds. • Immediate shut-down of seismic operations if a gray whale shows abnormal behaviours: a) consistent speeds of movement > 10 km/h, b) mother-calf pair separation of more than five body lengths, c) repeated multi-breaching with corresponding high speeds of movement from a potential disturbance source. • A precautionary shut-down will be initiated if specified marine mammal is observed to be on a course that will result in its entering the exclusion zone.
Poor visibility	<ul style="list-style-type: none"> • Seismic operations can continue in periods of poor visibility (night, fog, etc.) under certain defined circumstances. • To acquire a line in poor visibility, it must have been surveyed in good visibility conditions (either by the scout vessel or while sailing an adjacent line) during the preceding 6 hrs without any gray whale sightings. • If poor visibility hinders the scan of the entire line, then the line will not be acquired. • Operations will be shut-down for the low visibility/night period if whales are sighted during this scan. • In poor visibility, operations will not recommence after more than 20 min. of source activity due to the inability to conduct a visual scan.
Monitoring	<ul style="list-style-type: none"> • Shore-based distribution scans pre-, post- and during the survey not linked to operational criteria. • Two behaviour monitoring teams not linked to operational criteria.

The 2010 Piltun-Astokh seismic survey MMP: Monitoring

Behavioural monitoring

Two shore-based teams conducted behavioural monitoring prior to the start of the seismic survey (2 weeks), during the seismic survey, and after completion of the survey (2 weeks). To maximize the observation range, monitoring was conducted from two 3 m high wooden towers (Figure 5). Due to the increasing number of whales in the northern part of the survey area towards the end of the seismic survey, an adhoc observation station ('Blueberry Hill') was established north of the two towers to provide optimal coverage of the northern part of the A-zone. The southern station provided poor coverage of the southern part of the A-zone during acquisition of the most eastern A-lines, and behavioural station Blueberry Hill was used instead on two days towards the end of the seismic survey. Apart from monitoring the A-zone for presence of whales during acquisition of A-lines, a second objective of the behavioural teams was to determine if seismic activity and/or vessel proximity affected the behaviour of animals within the A-zone (Gailey *et al.* 2014). Consistent with previous behavioural monitoring during industrial activities in the Piltun area, univariate and multivariate analyses were conducted to assess the null hypothesis of no behavioural effects caused by continuous and/or pulse sounds and/or proximity of vessels during the 4D seismic survey (Gailey *et al.* 2007a, Gailey *et al.* 2007b, Johnson *et al.* 2007, Gailey *et al.* 2010, Gailey *et al.* 2014). The two behavioural teams conducted three types of observations, 1) regular scans to determine distribution and abundance of gray whales, 2) focal-animal follows to monitor respiration patterns and 3) theodolite tracking to obtain geographic positions of the whales over time. The teams operated independently of one another apart from the theodolite tracking. Focal-animal follows and theodolite tracking data were used to derive nine movement and seven respiration response variables. Behavioural data were consistent with those previously employed for behavioural monitoring of gray whales in the Piltun feeding ground (Gailey *et al.* 2011).

Environmental monitoring vessel

The monitoring vessel 'Pavel Gordienko' supported the onshore behavioural and acoustic teams in various ways. The vessel had the facilities required to function as a back-up acoustic receiving station in case of malfunction of the onshore station. A vessel-based behavioural team provided assistance to the onshore behavioural teams by monitoring the A-zone from the east (seaward) side of the PML. During seismic acquisition of A-lines the environmental monitoring vessel would advance about 1 km in front of the seismic vessel and 1 km east of the PML to scan the feeding ground for presence of gray whales. This monitoring routine would change when gray whales were observed in or near the A-zone, at which time the vessel would take a stationary position to continue monitoring the location of the whale. When no A-lines were being acquired, the vessel-based behavioural team would conduct focal follows of gray whales.

Distribution monitoring

As part of a multi-disciplinary gray whale study program off Sakhalin, distribution and abundance in the Piltun feeding area have been studied on an annual basis since 2002 from a total of 13 onshore distribution stations located along ~110 km of coastline (Vladimirov *et al.* 2013). Multiple distribution surveys were performed daily, weather permitting, within the southern Piltun feeding area before, during and after the 2010 4D Piltun-Astokh seismic survey activity. The survey objectives were to monitor gray whale distribution and abundance, and collect data for post-survey analyses of the potential influence of seismic activity on gray whale distribution and abundance (Muir *et al.* 2015b, Muir *et al.* 2016). A survey, consisting of a set of scans at the five southern distribution stations by two teams, was conducted before, during and after every seismic line acquisition, weather permitting. As the duration of a line-turn did not typically allow both a post- and pre-survey for the next line, a single survey was usually performed during the line-turn. Surveys were spaced throughout the day, weather permitting, during pre- and post-seismic monitoring. A third team conducted daily surveys at the other eight distribution stations north of the mouth of the Piltun lagoon (distribution stations 1-8), independent of seismic activity. Data from the northern team was collected to monitor distribution and abundance of gray whales before, during and after the seismic survey, but was not used for further analysis. A summary of all mitigation and monitoring measures is provided in Table 1.

The 2010 Piltun-Astokh Seismic Survey MMP: Implementation

Execution of the seismic survey

Onshore behavioural and distribution teams were mobilized on 30 May to conduct pre-seismic scans when some sea ice was still present; they demobilized on 13 July after completing post-seismic surveys. Weather conditions during the pre-seismic and seismic periods were generally favorable for visual observations. As expected, the number of whales in the survey area was very low up to the first week of seismic activity and gradually increased as the field season progressed. Although scheduled, effective onshore monitoring during the post-seismic was precluded by poor weather conditions.

The environmental monitoring vessel ‘Pavel Gordienko’ arrived in the Piltun area on 5 June, conducted systematic distribution surveys on 7 and 8 June, and deployed the archival and telemetry-based acoustic recorders on 8 June. The recorders were retrieved upon completion of the seismic survey.

The seismic survey vessel ‘Pacific Explorer’ arrived in the survey area in the early morning of 9 June. After it had scouted the survey area for the presence of sea ice, and satellite data had been analyzed, the region was declared ice free later that day. Deployment of the streamers and airgun array was completed by 12 June. The start of the survey, however, was delayed until 18 June due to technical issues related to rigging of the streamers and malfunctioning of the airguns in the cold water temperatures. The seismic survey was completed on 2 July. The line acquisition time for the 35 lines ranged between 1.26 hr and 2.80 hr depending on currents,

vessel speed, and length of line. The minimum time required for a line turn was 2.75 hr and was largely determined by currents, length of the streamers, servicing of the airgun array and ramp-up procedures (Table 2).

Due to lateral drag caused by tidal currents, seismic streamers are often not positioned in a straight line behind the seismic vessel but rather form small angles relative to the tow axis, a condition known as feathering. Due to the repeat nature of this survey, with requirements to precisely match earlier acquisition conditions, the feathering of the streamers had to be within 3 degrees of that encountered during the 1997 survey. On ten occasions, the amount of feathering exceeded the maximum tolerable discrepancy, resulting in the requirement to abort and/or re-acquire the lines.

Table 2: Seismic Line acquisition register (date/time is GMT+11).

Line	Line Category	Date	Start time ramp-up	Start time	End Time	Duration	Line completed	Data quality sufficient	Shut-down		Comments
									Technical	Visibility Whales	
33	B	16/06	23:10	23:56	0:46	0:50	N	N	X		
33	B	17/06	23:15	00:03	01:39	1:36	N	N	X		
11	A	18/06	05:15	06:03	08:48	2:45	Y	Y			
23	B	18/06	10:45	11:18	13:39	2:21	Y	Y			
32	B	18/06	22:02	22:45	00:41	1:56	Y	Y			
25	B	19/06	05:40	06:16	07:58	1:42	Y	Y			
2	A	19/06	09:35	10:04	11:51	1:47	Y	Y			
28	B	19/06	13:42	14:16	16:27	2:11	Y	N			
6	A	19/06	18:20	19:03	19:08	0:05	N	N		X	Fog: Insufficient visibility to observe A-zone & exclusion zone
29	B	19/06	22:07	22:46	0:54	2:08	Y	Y			
31	B	20/06	20:26	21:25	23:27	2:02	Y	Y			
22	B	21/06	04:15	5:00	5:02	0:02	N	N		X	Fog: Insufficient visibility to monitor exclusion zone
24	B	21/06	11:22	12:06	14:11	2:05	Y	N	X		Airgun misfiring
30	B	21/06	21:22	22:05	0:00	1:55	Y	N	X		Airgun misfiring
26	B	22/06	11:50	12:33	14:43	2:10	Y	Y			
12	A	22/06	16:00	16:48	17:34	0:46	N	N		X	Fog: Insufficient visibility to monitor A-zone
33	B	22/06	20:19	21:06	22:44	1:38	Y	Y			
21	B	23/06	08:30	9:08	11:38	2:30	Y	Y			
1	A	23/06	13:25	14:06	15:22	1:16	Y	Y			
23A	B	23/06	16:51	17:35	19:35	2:00	Y	Y			
24	B	24/06	01:20	1:48	3:38	1:50	Y	N	X		Airgun misfiring
30	B	24/06	08:40	9:19	11:31	2:12	Y	Y			
6	A	24/06	13:26	13:59	14:43	0:44	N	Y		X	Whale in A-zone

Table 2: Continued

Line	Line Category	Date	Start time ramp-up	Start time	End Time	Duration	Line completed	Data quality sufficient	Shut-down		Comments
									Technical	Visibility Whales	
12A	A	24/06	18:00	18:48	20:43	1:55	Y	Y			
14	B	25/06	03:35	4:03	6:08	2:05	Y	Y			
6	A	25/06	11:35	12:04	12:38	0:34	N	Y		X	Fog: Insufficient visibility to monitor A-zone. Shut-down at transition point
12	A	25/06	20:35	21:05	22:56	1:51	N	Y			Scheduled shut-down: Line could not be completed as night time prevented the A-zone from being monitored
15	B	26/06	02:05	2:31	4:21	1:50	Y	Y			
4	A	26/06	06:15	6:43	7:13	0:30	N	Y		X	Whales in A-zone: Shut-down at transition point
28	B	26/06	10:18	10:47	13:03	2:16	Y	Y			
5	A	26/06	14:35	15:02	16:50	1:48	Y	Y			
13	B	26/06	18:50	19:15	21:15	2:00	Y	Y			
17	B	27/06	03:35	4:05	4:43	0:38	N	Y			Section north of Molikpaq
3	A	27/06	07:25	7:52	9:24	1:32	Y	Y			
27	B	27/06	11:07	11:40	14:18	2:38	Y	N			Issue with data recording
7	A	27/06	18:19	18:46	19:16	0:30	N	Y		X	Whale north of seismic vessel displayed aberrant behaviour (breaching)
16	B	27/06	22:46	23:16	23:46	0:30	N	N	X		Feathering
9	A	28/06	05:47	6:13	8:31	2:18	Y	Y			
22	B	28/06	10:45	11:21	14:09	2:48	Y	Y			
6	A	28/06	15:47	16:26	17:33	1:07	Y	Y			
17	B	28/06	20:18	20:56	21:47	0:51	Y	N	X		Feathering. Section south of Molikpaq
10	A	29/06	05:51	6:29	8:49	2:20	Y	Y			
20	B	29/06	11:12	11:51	14:37	2:46	Y	Y			
4	A	29/06	18:45	19:22	20:46	1:24	N	Y		X	Whales observed in the A-zone
16	B	29/06	23:20	23:55	1:38	1:43	Y	Y			
12	A	30/06	05:30	6:00	6:55	0:55	Y	Y			
19	B	30/06	09:06	9:46	10:16	0:30	N	Y	X		Feathering
27	B	30/06	13:15	13:55	16:22	2:27	Y	Y			
4	A	30/06	21:05	21:44	22:17	0:33	Y	Y			
17	B	01/07	01:20	1:59	2:40	0:41	Y	Y			Section south of Molikpaq
7	A	01/07	06:20	6:50	9:08	2:18	Y	Y			
18	B	01/07	12:10	12:49	15:23	2:34	Y	N	X		Feathering

8	A	01/07	22:10	22:58	0:33	1:35	N	Y	Scheduled shut-down: Line could not be completed as night time prevented the A-zone from being monitored.
18	B	02/07	03:24	4:06	4:46	0:40	Y	Y	
8	A	02/07	08:30	8:56	9:52	0:56	Y	Y	
19	B	02/07	12:55	13:36	16:13	2:37	Y	Y	

Table 3: Time breakdown of Pacific Explorer in the period 13 June – 2 July 2010.

Activity	Days	%
Acquisition	3.4	17.1
Line change	3.6	18.1
Obstruction standby	0.1	0.7
Whale standby	0.6	3.3
Fog standby	1.8	9.3
Currents/feathering	1.8	8.9
Darkness standby	1.3	6.4
Mobilisation issues	5.0	25.4
Other	2.1	10.9
Total	19.7	100

Execution of the monitoring and mitigation plan

Most monitoring and mitigation measures were successfully implemented (Hurley 2010; IUCN 2010c). However, technical issues that delayed the start of the seismic survey, poor visibility, and increasing numbers of whales throughout the course of the operation made implementation of the MMP challenging. These issues could have prolonged the duration of the seismic survey considerably. Two alterations to the MMP were made during the execution phase of the plan to facilitate timely completion of the survey. Firstly, the rule preventing the acquisition of a seismic line if any gray whales were observed in the A-zone over the preceding 6 hrs (or 12 hrs for cow-calf pairs) was bypassed if the whales in the A-zone were observed to move outside this zone before the beginning of line acquisition. This was deemed justifiable as these whales would no longer be at risk of being exposed to sound levels exceeding 156 dB SEL. Secondly, the acquisition of a partial A-line up to the transition point was allowed to take place at night or in poor visibility if that line had been scouted in the previous 6 hrs, in keeping with the conditions applicable to full B-lines. Given that the pre-transition segment of a partial A-line did not generate an A-zone, this was considered acceptable since animals in the feeding ground would not be exposed to sound levels above the behavioural criterion. Both alterations were implemented as they were not considered by the SSTF to weaken the effectiveness of the mitigation program.

Sound source verification

The sound source verification test was conducted on 16 and 17 June during acquisition of test lines. Mini-AUARs were deployed at 0.75, 1.5, and 3 km from the most eastern seismic line

and recorded sound levels at the closest point of approach. The 180 dB re 1 μ Pa received level threshold was calculated to be 1.2 km away from the array. A 20% precautionary margin resulted in an exclusion radius of 1.46 km, which was rounded up to 1.5 km. The 190 dB re 1 μ Pa exclusion threshold for endangered pinnipeds was determined to occur at 540 m from the array (Racca *et al.* 2013).

Implementation of marine mammal shut-down criteria

A total of nine marine mammal-related seismic source shut-downs were ordered. Their causes were presence of whales in the exclusion zone (1 case), presence of gray whales in the A-zone during acquisition of A-lines (3 cases), display of aberrant behaviour by a gray whale (1 case), and inability to continue monitoring the A-zone and/or exclusion zone due to poor visibility (4 cases). These occurrences are summarized in Table 2 and described in more detail below.

A shut-down was implemented on one occasion during ramp-up due to the presence of a common minke whale (*Balaenoptera acutorostrata*) within the exclusion zone. No other shut-downs occurred during seismic acquisition as a result of gray whales, other cetaceans or Steller sea lions being observed within the exclusion zone. A shut-down was ordered in three cases when gray whales were observed within the A-zone during A-line acquisition. A single breach was observed during one of these events. A gray whale was observed to breach multiple times in the A-zone during seismic acquisition. The received sound levels at the whale's location were below the behavioural threshold (~ 140 dB 1 μ Pa rms) as the animal was positioned several kms north of the seismic vessel. It is not clear whether this behaviour was in some way a response to the seismic survey or the monitoring vessel, which was at least 1 km away from the animal, but because multiple breaching was classified as aberrant behaviour in the MMP, a shut-down was implemented accordingly. In three cases, acquisition of A-lines had to be aborted due to insufficient visibility (fog) to effectively monitor the A-zone. During acquisition of a B-line the visibility deteriorated so that the exclusion zone couldn't be effectively monitored. As the line had not been scouted in the previous 6 hrs, a shut-down was implemented. In addition to these 9 whale-related shut-downs, the southern part of two A-lines was acquired at night up to the transition point, at which the airguns were shut down. As these shut-downs were a result of implementation of the MMP, they were categorized as 'darkness standby' (Table 3).

Time budget of MMP

Table 3 outlines the seismic vessel's (Pacific Explorer) activities. Mobilization issues from 13-18 June resulted in 5 days delay ($\sim 25\%$ of the total vessel time). The categories 'whale standby', 'fog standby' and 'darkness standby' were considered delays as a result of implementing the MMP. The MMP added 3.7 days to the survey duration (19% of the total vessel time). However, relatively few whales were in the area at the onset of the survey period, and very few fog days occurred during 13-18 June. Therefore, the standby time due to fog and presence of whales would have decreased if the survey had started on the original start date (13 June) instead of being delayed by technical issues.

Figure 6: Whale path annotated with estimated received sound levels (per-pulse SEL) from the seismic source acquiring a survey line (purple track to the right). The track of the monitoring vessel “Pavel Gordienko” is shown in blue near the PML. The simultaneous start points of the three tracks are labelled, and black dots indicate the relative locations of source and whale at time of maximum exposure. Shown on shore are three behavioural monitoring stations.

The 2010 Piltun-Astokh Seismic Survey MMP: Effectiveness

Estimation of sound levels on whale paths

One objective of the MMP was to obtain a better understanding of the impacts of pulsed and continuous noise on gray whale behaviour. To that end, the variables that may affect whale behaviour must be quantified at the whale locations. During the survey, positional information was collected for numerous whale paths by two behavioural monitoring teams and the locations of all vessels in the immediate area were recorded by AIS/GPS logging. From these data it was possible to model sound levels from the airgun source and vessels as received at the whale locations. This estimation process yielded detailed time histories of sound levels at whale

locations for all recorded whale tracks. Figure 6 provides an example of sound level exposure of a gray whale during the seismic survey. These data were used to assess behavioural responses on an individual level, as well as on a population level (Gailey *et al.* 2014). Further details on sound level estimations at whale locations and analyses of behavioural responses during these tracks are provided in Racca *et al.* (2014) and Gailey *et al.* (2014), respectively.

Impact of seismic sounds on gray whale distribution and behaviour

Focal-animal follow and theodolite tracking data were analyzed by assessing movement and respiration response variables relative to acoustic metrics, environmental, temporal, spatial and behavioural information, as well as vessel sound levels and distances, to investigate disturbance effects of seismic activity in the proximity of the near-shore feeding habitat of gray whales.

While seismic sounds were not significantly associated with movement and respiration parameters on a population level, a number of behavioural response variables were associated with proximity of vessels, suggesting some level of non-seismic anthropogenic effect (Gailey *et al.* 2014). Power analyses demonstrated the study's ability to detect large effects (>50%), but not to identify more moderate or subtle changes in respiration and movement (Gailey *et al.* 2014). Although some individual responses in movement patterns were observed, the results from the behavioural analysis suggested the seismic survey didn't have a large impact on the movement or respiration patterns of the population of gray whales as a whole (Gailey *et al.* 2014).

Two separate distribution analyses were conducted to investigate cumulative sound exposure from seismic activity relative to changes in both sighting distance from shore and in mean daily gray whale density surfaces of 1 x 1 km grid cells. No effects of cumulative sound on distance from shore were observed (Muir *et al.* 2015b). However, higher cumulative sound levels in the previous 24 to 48 hrs were significantly correlated with decreased grid cell densities and models predicted highest occupancy probabilities and higher densities in the northern part of the study area that corresponded to moderate cumulative seismic sound levels. These effects of cumulative sound from the seismic activity on occupancy and densities suggest avoidance of higher cumulative sound exposure levels associated with a prolonged period of acoustic disturbance (Muir *et al.* 2016). As pointed out by Muir *et al.* (2016), a limitation of the distribution analyses was that data on prey abundance were not available and therefore this important predictor of whale distribution was not included in the models.

The main mitigation measure of completing the survey as early in the feeding season as possible was relatively successful but inevitably resulted in reduced power to assess the impacts of seismic sound exposure on gray whale distribution and behaviour. Few whales were present, particularly during the pre-seismic period and the first week of the seismic survey. This resulted in relatively few observations to compare with those made during the seismic period, and limited the ability to assess potential changes in distribution and behaviour relative to seismic sound exposure. Analyses were further limited by poor weather conditions in the post-seismic survey monitoring period that resulted in nearly no survey effort, and limited statistical power to compare whale distribution and behaviour during and after the seismic survey activity.

In terms of population consequences, important observations are that the body condition of animals appeared to have improved over the 2010 feeding period, with only 11.1% of the observed individuals having 'low' body condition scores at the last sighting of the 2010 feeding season compared to a mean of $14.3 \pm \text{SD } 4.64$ from 2002-2012 (Tyurneva *et al.* 2013). The seismic survey is not thought to have affected calf production, an important population parameter, judging by the fact that 15 calves were sighted in 2011 (the highest number over the period 2001-2012) and 9 in 2012 (Tyurneva *et al.* 2012, 2013).

These analyses were extensively discussed during various SSTF meeting (IUCN 2010a, b, c, IUCN 2011). The SSTF strove to evaluate the implementation and effectiveness of applied mitigation measures, and recognized the largely satisfactory field enactment of the MMP.

Findings And Recommendations

- (1) Careful planning in development and implementation of the MMP by a multi-disciplinary technical team of both independent and company-contracted scientists led to an effective plan that appears to have met the objective of reducing risks to gray whales from the seismic survey (IUCN 2010c, Nowacek *et al.* 2013). As explained, the objective of obtaining insight into the potential impacts of future seismic surveys could be met only partially, because of the overarching mitigation imperative of completing the work before substantial numbers of whales arrived at the feeding grounds (see Item 5 below).
- (2) Implementation of this MMP was logistically and technically challenging, as it involved several vessels, multiple shore- and vessel-based monitoring teams, various channels of communication and critical reliance on technical equipment in a remote environment.
- (3) Future MMPs developed for gray whales on the Piltun feeding grounds should incorporate into the shut-down criteria behavioural observations of animals prior to approaching or entering the A-zone. Given that the primary objective was to minimize disruptions to feeding activity, animals observed as simply traversing the habitat even within the A-zone and not displaying aberrant behaviour should not be considered in determining the requirements for shut-down, since this may lengthen the survey unnecessarily.
- (4) Although the shape of the A-zone was different for each A-line, the A-zone used in this MMP was static, in the sense that it was independent of the location of the seismic source in relation to the position of an observed whale. Animals in the A-zone were not necessarily exposed to sound levels exceeding 156 dB SEL if they were sufficiently far to the north or south of the seismic vessel at the time. Due to the directionality of the seismic array, the highest sound levels were generated broadside to the source, thus creating a relatively narrow envelope of sound exposure abeam the vessel. A dynamic A-zone could be applied instead, encompassing the broadside beam of the source with a buffer distance fore and aft of the seismic vessel. This buffer would have to be sufficiently large to prevent animals from being exposed to pulse levels exceeding 156 dB SEL, but could still reduce the duration of the survey by eliminating unnecessary shut-downs for animals far enough ahead of or behind

the seismic vessel.

- (5) Due to the relatively short duration and completion of the survey early in the feeding season, when the number of gray whales in the area was still low, relatively few visual observations were made of individuals exposed to seismic pulses. Furthermore, observations in the period following the seismic survey were limited due to poor weather conditions. These factors reduced the statistical power to detect changes in whale behaviour and distribution in relation to seismic activity. An enhanced understanding of data requirements and analytical approaches, obtained through additional power analyses during the MMP development phase, would help improve the design of the monitoring program to support meaningful conclusions.
- (6) Use of the independent observer gave implementation of the MMP credibility, i.e. interested stakeholders were provided with an independent means of assessing the challenges and effectiveness of implementation.
- (7) Limited behavioural or distributional responses of whales to seismic sound exposure were observed, suggesting that the mitigation program for this particular seismic survey was successful in minimizing the impacts on gray whales. However, various kinds of industrial activity take place in or near the Piltun feeding grounds, and successful mitigation of 1 particular event, such as the 2010 Astokh 4D seismic survey, is not adequate by itself. The potential effects of those other activities need to be assessed and managed to minimize the cumulative disturbance to the whale population. A case in point is another seismic survey that was conducted in the Piltun region during the 2010 feeding season by Rosneft Shelf Far East, which acquired seismic data in the Lebedinsky license area (SakhalinV project). Although some mitigation and monitoring measures reportedly were applied, this seismic survey was conducted in the littoral region and within the near-shore feeding grounds when the abundance of gray whales was at its peak (Rutenko *et al.* 2012b). The cumulative effects of industrial activities on the gray whale population are not well understood, in part due to the general difficulty of assessing impacts of multiple and aggregate stressors on wild populations. The development of frameworks for cumulative impact assessment is an area of active research (example Moore *et al.* 2012).

Conclusion

The 2010 Piltun-Astokh seismic survey ranks as one of the most extensively mitigated marine seismic surveys to date (Nowacek *et al.* 2013). Though some adjustments to the MMP were introduced in the field to address operational circumstances, the primary mitigation measures were successfully implemented. This seismic survey was exceptional in some ways because of its close proximity to a spatially limited, near-shore feeding area of a Critically Endangered population of whales that could be monitored from shore. Although elements of this MMP can be replicated in other situations, including offshore seismic surveys, there are likely to be few opportunities to implement an identical plan elsewhere. Indeed, most seismic surveys may not

warrant the application of a behavioural mitigation threshold unless endangered or threatened populations or species inhabit the region.

Although some whale responses to seismic sound exposure, in the form of small changes in distribution patterns, were detected in the post-season analysis of collected data, the biological significance of such changes on the local population of whales was likely to be minimal.

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Chapter 6

Characteristics of seismic survey pulses and the ambient soundscape in Baffin Bay and Melville Bay, West Greenland

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Abstract

In 2012 a seismic survey campaign involving four vessels was conducted in Baffin Bay, west Greenland. Long-distance (150 km) pre-survey acoustic modeling was performed in accordance with regulatory requirements. Four acoustic recorders, three with hydrophones at 100, 200, and 400 m depths, measured ambient and anthropogenic sound during the survey. Additional recordings without the surveys were made from September 2013 to September 2014. The results show that 1) the soundscape of Baffin Bay is typical for open ocean environments and Melville Bay's soundscape is dominated by glacial ice noise; 2) there are distinct multipath arrivals of seismic pulses 40 km from the array; 3) seismic sound levels vary little as a function of depth; 4) high fidelity pre-survey acoustic propagation modeling produced reliable results; 5) the daily SEL did not exceed regulatory thresholds and were different using Southall *et al.* (2007) or NOAA weightings (NMFS 2016); 6) fluctuations of SPL with range were better described by additive models than linear regression; and 7) the survey increased the 1-min SPL by 28 dB, with most of the energy below 100 Hz; energy in the 16000 Hz octave band was 20 dB above the ambient background 6 km from the source.

Keywords: seismic airgun; ambient noise; SPL; Baffin Bay; Melville Bay; SEL.

Introduction

In 2010, five petroleum exploration license blocks were awarded in Baffin Bay, west Greenland. Some of these blocks have considerable overlap with narwhal protection areas and are proximal to the Melville Bay Nature Reserve (Figure 1). As part of the environmental permitting process for seismic surveys in Greenland, the Danish Centre for Environment and Energy (DCE) issued Environmental Impact Assessment requirements that include acoustic modeling and monitoring guidelines (Kyhn *et al.*, 2011). These guidelines define many of the responsible practices with respect to marine mammals and seismic surveys that were subsequently described by Nowacek *et al.* (2013). The main mitigation measures in these guidelines are 1) establishing the radius of exclusion zones with high-fidelity acoustic modeling; 2) visually and/or acoustically monitoring exclusion zones to minimize auditory injury to marine mammals; and 3) turning off active sources when mammals are detected in exclusion zones. The DCE guidelines (Kyhn *et al.*, 2011) apply the dual criteria recommended by Southall *et al.* (2007): a maximum peak sound pressure level (SPL) and a 24-hour sound exposure level (SEL) limit. Seismic surveys are usually performed using arrays of airguns spread over an area on the order of 100 m² and are therefore not point sources. The range from an airgun array where the peak sound pressure level criterion of 230 dB re 1 μ Pa for cetaceans is exceeded (if at all) is at most on the order of tens of meters, indeed comparable to the size of the airgun array itself (Caldwell and Dragoset, 2000; Gisiner, 2016). Thus, the criterion of concern for defining exclusion zones is the 24-hour SEL. The 24-hour SEL thresholds recommended in Southall *et al.* (2007) are weighted for the hearing bands of mammal groups; the SEL criterion is typically exceeded at ranges from the airgun array on the order of hundreds of meters (e.g., Tashmukhambetov *et al.*, 2008; Breitzke and Bohlen, 2010; Matthews, 2012). It is widely accepted that applying mitigation zones based on these thresholds minimizes the risk of injuring marine mammals (Gordon *et al.*, 2003; Wartzok *et al.*, 2003; Southall *et al.*, 2007; Nowacek *et al.*, 2013).

Seismic airgun pulses can be perceptible above the background ocean sound at distances in the order of hundreds of kilometers (e.g., Bohnenstiehl *et al.*, 2012a; MacGillivray *et al.*, 2014; Blackwell *et al.*, 2015) and even farther if the energy propagates in a deep sound channel (Thode *et al.*, 2010; Nieu Kirk *et al.*, 2012; Blackwell *et al.*, 2015). At ranges between the injury exclusion zones and the limits of perception for seismic sound, animals may experience temporary threshold shift (TTS), behavioral disturbance, and masking effects (Gordon *et al.*, 2003; Southall *et al.*, 2007; Nowacek *et al.*, 2013). The sound levels that induce behavioral responses from marine mammals cover a wide range of sound pressure and sound exposure levels and are dependent on factors such as the type of activity an animal was engaged in when exposed to the sound (e.g., Richardson *et al.*, 1986; Wartzok *et al.*, 2003; Ellison *et al.*, 2012; Robertson *et al.*, 2013). It is extremely difficult, therefore, to establish relevant metrics and appropriate thresholds to minimize behavioral effects (Southall *et al.*, 2007; Kyhn *et al.*, 2011; Finneran and Jenkins, 2012; Wood *et al.*, 2012; NOAA 2013; Wisniewska *et al.*, 2014). Behavioral response studies aim to develop dose-behavioral response relationships reflecting the range of sound levels

required to elicit a response within a population (e.g., Kastelein *et al.*, 2013a) or the magnitude of response as a function of the stimulus (e.g., Kastelein *et al.*, 2013b). The sound levels that have been reported to start eliciting behavioral responses range between 100 and 180 dB re 1 μ Pa SPL (Finneran and Jenkins, 2012; Wood *et al.*, 2012; Shannon *et al.*, 2016; Carroll *et al.*, 2017). The SPL depends on the averaging time used, which can lead to a range of possible values for the same pulse depending how the pulse length is determined (Madsen, 2005). It is important to document the variability in the pulse length and SPL with in situ data.

Man-made sound has the potential to mask ecologically relevant sounds, especially when the frequency bands of the sound sources overlap. Sounds that are ecologically relevant to marine animals include conspecific calls, predator and prey sounds, natural sounds used for orientation, and echolocation calls from odontocetes (Clark *et al.*, 2009). Seismic airgun arrays emit high-intensity low-frequency sound impulses with peak frequencies of near 50 Hz (Dragoset, 1990; Caldwell and Dragoset, 2000). They are expected to have minimal impacts on marine mammals, such as odontocetes, that have limited hearing sensitivity at these low frequencies (NRC 2005; Southall *et al.*, 2007; NMFS 2016). However, Goold and Fish (1998) report frequencies of up to 8 kHz above the ambient background at a distance of 8 km from a 2120 in³ seismic array in 50–100 m deep water, Madsen *et al.* (2006) report measured per-pulse SPLs in the 10 kHz 1/3-octave-band greater than 110 dB at a range of 1.4 km from a 2590 in³ seismic array in deep waters in the Gulf of Mexico, and Hermannsen *et al.* (2015) show energy above 10 kHz from single airguns at a range of 1300 m in 15 m deep water.

In summer 2011, license holders submitted four seismic survey applications to the DCE. As part of the Environmental Impact Assessment process, each proponent's acoustic modeling methods and results (e.g., Matthews, 2012) were reviewed by the DCE, and the cumulative effects of all surveys were assessed. Various data gaps were identified, such as 1) limited documentation of the propagation of seismic airgun pulses around Greenland; 2) limited ambient sound data for Baffin Bay and Melville Bay; 3) limited knowledge of the variation in seismic array sound levels as a function of depth; 4) uncertainty about the importance of high-fidelity inputs for acoustic models (e.g., temperature/salinity profiles, bottom contours, and the sub-bottom geo-acoustic structure); and 5) the temporal and spatial variation of marine mammal distribution in Baffin Bay and Melville Bay (Wisniewska *et al.*, 2014). Comparing measured and modeled sound propagation as a function of depth was noted as especially important, since cold fresh water from melting glaciers creates a strong sound speed minimum at 30–80 m depth, which is expected to trap and propagate low-frequency sounds for long distances in the sound duct.

To address these data gaps, we conducted a multi-year acoustic monitoring program. As part of Shell's seismic survey in the license areas, three vertical array moorings with hydrophones at three measurement depths were deployed in summer 2012 (Figure 1, also see Section II.A). We also deployed one bottom-mounted autonomous recorder in Melville Bay from mid-August to mid-September 2012. During August and September 2012, two seismic source vessels conducted a 3-D seismic survey with 3480 in³ airgun arrays near the vertical arrays, including two passes within 110 m slant range of the top hydrophones. The modeled broadside zero-to-

peak sound pressure source level of the arrays was 247.3 dB re 1 μ Pa with a modeled per-pulse sound exposure level of 227.8 dB re 1 μ Pa²-s (Matthews, 2012). Five recorders were deployed in September 2013 to study the summer ambient soundscape and to characterize a lower-energy shallow-hazards seismic survey conducted with a 140 in³ array (modeled broadside zero-to-peak sound pressure source level of the array was 239.3 dB re 1 μ Pa with a modeled per-pulse sound exposure level of 214.5 dB re 1 μ Pa²-s) (Matthews, 2013). Two recorders with hydrophones at mid-water column depth were deployed overwinter from 29 Sep 2013 to 6 Sep 2014 to capture the soundscape over a full year (see Section II.A).

Here we report on the new knowledge derived from the monitoring program through an analysis of the license block and Melville Bay recordings. We present 1) propagation conditions of seismic pulses in Baffin Bay; 2) an overview of ambient sound characteristics, total sound levels, and spectral content associated with seismic pulses in Baffin and Melville Bay; 3) variation in seismic airgun sound levels as a function of depth; 4) a comparison of modeled and measured sound levels at ranges up to 65 km from the source; 5) cumulative sound exposure levels; 6) a comparison of different SPL metrics for predictions of ranges to behavioral disturbance of marine mammals; and 7) the measured spectral content of the pulses as a function of range to the seismic source. Due to the large amounts of data collected in this project, we have provided figures and tables that illustrate points on additional recorder channels in the Supporting Information section. The data from this project also generated extensive new information on the seasonal presence of marine mammals in Baffin Bay, which is reported in Frouin-Mouy *et al.* (2017).

Methods

This section describes the autonomous recorder deployments and the methods used for analyzing the data and acoustic propagation modeling. With respect to acoustic terminology, this manuscript uses the terms recommended in the final draft of ISO standard 18405:2017. Specifically, sound pressure level is 20 times the base-10 logarithm of the root mean squared pressure summed over a specified time window and is abbreviated as SPL or $L_{p, \text{duration rms}}$ where ‘p’ stands for pressure and ‘duration’ is the averaging window length. The maximum of the pressure signal, in dB re 1 μ Pa, is referred to as peak sound pressure level or $L_{p, pk}$. The 1/3-octave-band used in this analysis followed the 1/10th decade (deci-decade) definition of 1/3-octaves.

Recorders and deployments

Autonomous Multichannel Acoustic Recorders (AMARs, JASCO Applied Sciences) were deployed at Stations BB1–BB4 (Figure 1, Table S-1) between 29 Jul and 2 Oct 2012. Stations BB1–BB3 were bottom-mounted vertical arrays (Figure 2), with hydrophones at 100, 200, and 400 m water depths. The recording depths were chosen as a compromise between the expected propagation paths (see Section II.C), water column coverage, and eliminating interference with the seismic arrays. At these three stations, the top hydrophone (100 m depth) sampled continuously at 64 kilosamples per second (ksp/s) to record seismic airgun pulses and marine mammal calls. The

two lower hydrophones (200 and 400 m depth) sampled continuously at 8 ksps, primarily to record seismic airgun pulses. All three hydrophones were sampled by the same AMAR. The 8 ksps sample rate for the lower hydrophones was chosen to maximize the recording duration within the memory capacity of the system (1.792 TB). We chose not to duty cycle these recordings so that the recordings would contain complete overpasses of the seismic vessel at all depths. Station BB3 was located within 3 km of pre-survey modeling Site 3 (Matthews, 2012) to permit comparisons between the measured and modeled data (Figure 1). At Station BB4, located within Melville Bay, an AMAR was deployed at the seabed (130 m) with a single omnidirectional hydrophone sampling at 64 ksps.

AMARs were deployed at Stations BB5–BB9 (Figure 1, Table S-1) between 31 Aug and 30 Sep 2013. These systems were fitted with GTI-M8E hydrophones which, due to the shorter monitoring period allowed for higher sampling rates, alternated between sampling rates of 64 and 375 ksps. The hydrophones were positioned between 300–500 m, in each case near mid-water column for the chosen locations (Table S-1). To collect a year-long dataset without seismic activity, AMARs were deployed at Stations BB6 and BB10 from late September 2013 to early September 2014 (Figure 1, Table S-1). Each year-long AMAR was fitted with a GTI-M8E-V35 dB omnidirectional hydrophone and cycled between 64 and 375 ksps, as well as periods of sleep. The details of hydrophone sampling configurations and sensitivities are given in Table S-2 and Table S-3.

Figure 1: Recorder stations in summer 2012 (green circles/darker gray), summer 2013 (orange circles/light gray), and overwinter 2013–2014 (black triangles), as well as pre-survey modeling locations (purple hexagons). Narwhal protection area data from Kyhn *et al.* (2011).

Figure 2: Overview of the mooring configuration used in 2012. The bottom hydrophone was located at ~ 400 m water depth with the recorder located ~5 m below it. The other hydrophones were located at 200 and 100 m depth. The streamlined sub-surface float was at 90 m depth.

Acoustic data analysis

Acoustic data were quantified using three standard metrics: peak sound pressure level, sound exposure level (SEL), and sound pressure level (SPL) (see for example Madsen, 2005 for definitions of these metrics). The broadband SPL, as well as the SPL, in each 1/3-octave-band were computed. The metrics were computed for each minute of data to characterize the total sound levels and separately for each detected seismic pulse to characterize the short impulses. The one-minute deci-decade SPLs were converted to deci-decade SELs by adding $10 \cdot \log_{10}(60 \text{ seconds})$ and combined to assess the frequency-weighted sound levels (Southall *et al.*, 2007) or to compute the sound levels in octave bands so seismic sound levels could be discussed as a function of frequency. The 1 Hz power spectral densities averaged over 1 minute were computed and are presented in the Section III.A and the Supplementary Information as long term spectrograms, percentile levels, and spectral probability densities (see Merchant *et al.*, 2015 for a discussion of these methods).

Our analysis used exceedance percentile levels to quantify the distribution of recorded sound levels. Following standard acoustical terminology, the n th percentile level (L_n) is the level (i.e., power spectral density level, SPL, or SEL) exceeded by $n\%$ of the data. $L_{\max}$ is the maximum recorded sound level. L_{mean} is the linear arithmetic mean of the sound power, which can differ significantly from the median sound level L_{50} . The exceedance percentiles are often presented as statistical sound levels using box-and-whisker plots (e.g., Figure 5). In such plots, the bottom and top of the ‘box’ are defined by the 75th and 25th percentile sound levels respectively, and a line through the middle of the box shows the median level. Whisker lines extending above and below the box show the total range of measured data, with short hash marks to indicate the 95th and 5th percentiles. The mean (L_{mean}) value is shown with a separate line across the plot.

Seismic survey pulses were identified using a variation on the Teager-Kaiser (TK) energy detector (Kaiser, 1990). The detector created an ‘energy’ time-series as the square root of the sum of the squared pressure signal over a period of 0.03 s. A detection was determined to have occurred when the square of this time series (sample X_i) was greater than the product of its neighbors by a chosen threshold (Equation 1).

$$X_i^2 - X_{i-1} * X_{i+1} > T \quad (1)$$

The pulse limits were defined by searching for the maximum energy in the neighborhood of each detection. Two versions of the detector were implemented for this study. The first version used the 90% energy duration method of analyzing man-made impulsive sounds (T90 SPL, e.g., Blackwell *et al.*, 2004; Thode *et al.*, 2010) by searching over a 7 s window and finding the period that contained 90% of the energy (7 s was required due to the extensive multi-path arrivals, see Figure 7 and Figure 8). The second version limited the duration of the impulse to the integration time of mammalian hearing (Madsen, 2005; Tougaard *et al.*, 2015) by searching over a 0.5 s time window centered on the TK-detection and finding the 0.125 s period with the maximum energy. Multi-path arrivals from a single airgun pulse were separated into distinct impulses for

analysis when we used the second approach. We chose the 0.125 s window based on Tougaard *et al.* (2015) because it is also the standard used in terrestrial sound level meters for fast-time weighting (ANSI S1.4-1983, R2006) and hence will be simpler for other teams to replicate in the future. The results of these two approaches were compared with the total 1 min sound levels computed from the same time periods.

The data were pre-conditioned using a 10 Hz high-pass digital filter to remove very low-frequency electrical noise caused by an improper power supply to the current-loop circuits of the hydrophones. The finite impulse response filter was designed with the MATLAB (The Mathworks Inc, Natick Ma) *Filter and Window Design Application*, with a 7 Hz stop frequency, a 10 Hz pass frequency, and 60 dB of stopband attenuation using the ‘Kaiser Window’ design option. The filter had 77342 points, and it did not significantly affect the measured signal levels above 10 Hz. Analysis of seismic pulses received 40 km from the source before the electrical noise began (5–6 Aug) showed up to a 0.2 dB difference in the per-pulse SPL and SEL, and up to a 1.5 dB difference in the peak sound pressure level. Processing of the wav file recordings was performed using the PAMlab software suite (JASCO Applied Sciences). Post processing of the PAMlab outputs and plot generation was performed using custom MATLAB scripts.

Seismic source and acoustic propagation modeling

Acoustic propagation modeling was a four-part process: 1) modeling of the airgun source; 2) modeling per-pulse sound exposure level propagation loss using a range-dependent parabolic equation model, 3) combining the source level and propagation loss to estimate the per-pulse SEL at the water volume around the source, and 4) converting the per-pulse SEL to SPL. The first two steps were performed at individual deci-decade center frequencies between 10 and 2000 Hz, and the contributions of each band were summed during the final step. We used the Airgun Array Source Model (AASM, JASCO Applied Sciences) to estimate the source signature of each airgun in the array by simulating the physics of bubble expansion and interactions with adjacent bubbles. The frequency dependent source level and beam pattern of the array were estimated by convolving the signatures of the individual airguns taking into account the geometry of the array (MacGillivray, 2006; Matthews, 2012). The Marine Operations Noise Model (MONM, JASCO Applied Sciences) was used to perform parabolic equation propagation loss modeling. MONM is based on the U.S. Navy’s Range-dependent Acoustic Model (Collins, 1993), modified to use complex density to approximate shear wave conversion energy loss at the seafloor (MacGillivray, 2006; Matthews, 2012; MacGillivray, 2013).

Propagation loss estimates are affected by the bathymetry, water column sound speed profile, and acoustic properties of the seabed. Pre-survey modeling (Matthews, 2012) was performed using sound speed profiles from the Generalized Digital Environmental Model (GDEM) database (Teague *et al.*, 1990), bathymetry from the SRTM 30 data set (Rodriguez *et al.*, 2005), and a five-layer seabed geo-acoustic profile based on available literature (Table S-4). The sound speed profile in this area has a strong sound speed minimum at ~60 m depth because of cold fresher water lying over warmer more saline water (e.g., Figure S-3). Therefore,

we expected that sound would refract towards the sound speed minimum and that there would be higher sound levels at 100 m recording depth compared to the lower recording depths (see Sabra *et al.*, 2016 for an introduction to long range underwater sound propagation). Due to the width of the measured sound duct (~ 15 m/s change from 30 to 100 m depth) the measured sound levels at higher frequencies may slightly less than could have been measured at 60 m at long ranges.

Per-pulse SELs were converted to T_{90} SPLs using a range dependent estimate of the pulse length. The pulse length was estimated by generating a synthetic pressure waveform for the airgun array through a Fourier synthesis of the waveform. The vertically and azimuthally directional starting field for the sound propagation model was generated in a 1-Hz frequency bin from 10–2000 Hz, based on the source signature computed by AASM and the relative position of each array element. The propagated sound field was summed across frequency, and then an inverse Fourier transform was performed to obtain the modeled waveform. The pulse length was obtained from the modeled waveform to produce a per-pulse SEL to SPL conversion factor. During the pre-survey modeling, two conversion factors were estimated, one eastward from Station BB1 and the other westward from BB1. For the post-survey analysis, a conversion factor along bearing of 030° (northeast) from Station BB1, towards BB3, was computed.

During data analysis, the measured and modeled sound levels were compared. Further modeling was performed to investigate if the differences between the measured and modeled sound levels could be reduced by increasing the frequency resolution of the modeling, running the model with the measured sound speed profiles, or using the bathymetry measured by the seismic vessels.

2012 and 2013 Greenland seismic surveys

Seismic surveys were conducted in the Shell-operated license areas in 2012 and 2013. The 2012 3-D survey was conducted by the *Polarcus Amani* and *Polarcus Samur* from 2 Aug to 15 Oct. In that year, each vessel towed two 3480 in³ seismic arrays (Figure S-2). The arrays on each ship were operated alternately so that the average sounding rate per ship was 10–12 s. The median survey speed was 2.25 m/s, or 8.1 km/h. The vessels operated independently throughout the survey. The ships occasionally operated in the same area on parallel acquisition lines, separated in time by a 4 h delay (32 km separation). Approximately 228,000 pulses from the *Amani* and 220,000 from the *Samur* were recorded. The median ranges of the *Amani* to Stations BB1, BB3, and BB4 were 42, 106, and 124 km, respectively (Table 1, Figure 3). The median ranges to the *Samur* were 36, 62, and 105 km, respectively. The vessel tracks that passed closest to Station BB1 on 4 Sep and BB3 on 18 Sep are examined. Station BB2 measurements were similar to BB1, so only BB1 is analyzed in detail.

Two other seismic surveys occurred in summer 2012 in Baffin Bay. ConocoPhillips, DONG Energy, and Nunaoil jointly conducted a 2-D survey from 25 Aug to 24 Sep in the license area north of the Shell license area. This survey's closest point of approach was ~ 40 km to Station BB3 and 120 km to BB4. Maersk Oil conducted a 3-D survey from 6 Aug to 1 Oct in the

license area southeast of the Shell license area. This survey's closest point of approach was 100 km to Station BB1 and at least 200 km from BB4 (Wisniewska *et al.*, 2014).

From 15 Sep to 8 Oct 2013 the *Fugro Discovery* conducted a localized shallow-hazards survey for Shell Oil by using a 140 in³ array (Table S-5, Figure S-1). Shallow hazards surveys detect features that may impact proposed oil and gas operations such as gas vents, abnormal pressure zones, and faults lines. Here we present the data from Station BB6 as an example of measurements that were 40 or more kilometers from the shallow-hazards survey, and BB7 as an example of recordings within the region of the survey. The two summer data sets with seismic surveys are compared with the year-long data from Stations BB6 and BB10.

Table 1: Minimum, median, and maximum distances from the *Amani* and *Samur* to Stations BB1, BB3, and BB4 in summer 2012.

Ranges from survey vessel to station	Minimum distance (km)	Median distance (km)	Maximum distance (km)	Median daily closest point of approach (km)
Amani to:				
BB1	0.1	42	89	16
BB3	0.02	106	153	40
BB4	68	124	158	95
Samur to:				
BB1	0.7	36	90	14
BB3	0.6	62	153	25
BB4	68	105	158	95

Figure 3: Survey lines of the *Amani* and *Samur* in summer 2012.

Results and discussion

Soundscapes of Baffin and Melville Bays

The various sets of acoustic data acquired during this project are characterized by different combinations of man-made and natural sounds (Figure 4): 1) the year-round recording at Station BB6 shows minimal man-made sounds; 2) the September 2013 recording at BB7 reveal few man-made sources until the start of the shallow hazards survey on 15 Sep; 3) the nearshore recordings in Melville Bay (BB4) from 2012 are dominated by glacial ice sounds; and 4) the BB1 recordings from 2012 prominently feature the 3-D seismic survey. When the seismic surveys started on 2 Aug 2012 and 15 Sep 2013, the average sound levels near the operations increased. The average 1-min SPL at Station BB1 was 106 dB re 1 μ Pa prior to 2 Aug 2012 and 134 dB re 1 μ Pa after that date, with most of the increase at frequencies below 100 Hz (Figure 4, Panel 4). The received sound levels at that station increased and decreased as the survey vessel approached and departed. Other stations (e.g., Station BB3, Figure S-4) had similar results. The sounds from the surveys in the other license areas are not discernible in these figures.

Figure 4: Summary of the received sound levels in Baffin Bay for four sound scenarios: 1) Station BB6 in overwinter 2013–2014 with minimal man-made sounds; 2) BB7 in summer 2013 at 3–100 km from a shallow hazards survey that started 15 Sep; 3) BB4 near glacial ice in Melville Bay in 2012; and 4) BB1 in summer 2012 at 0.1–90 km from the 3-D seismic survey that started 2 Aug. The bottom section of each figure shows long-term spectrograms and the top section corresponding band-level time-series plots.

The summer 2012 stations were deployed 29 and 30 Jul and retrieved 29 Sep to 2 Oct (Table S-1). Since the seismic survey started on 2 Aug, there were little data available from 2012 to assess the natural ambient soundscape in Baffin Bay. The summer 2013 and overwinter 2013–2014 recordings provide data for this purpose (Figure 5, Figure S-4, Figure S-6, Figure S-8). Figure 5 shows the distribution of 1-min SPLs in four of these recordings. Broadband (10–32000 Hz) and four decade bands are shown. The 10–100 Hz band normally contains sounds from natural and anthropogenic seismic sources, calls from the very large baleen whales, as well as possible pseudo-noise from flow over hydrophones and cable strum. Large vessels, seismic surveys, baleen whales, and wind and wave action are the primary sources of sound in the 100–1000 Hz band. The 1000–10000 Hz band contains sounds from wind and wave action and potentially whistles from pilot whales and narwhals. The 10000–32000 Hz band normally contains energy from whistles, echolocation clicks, and rain (see Cato, 2008; Hildebrand, 2009 for summaries of ocean noise).

Station BB6 is representative of ambient sound level measurements in Baffin Bay with a median SPL of 102 dB re 1 μ Pa in summer 2013 and 100 dB re 1 μ Pa overwinter 2013–2014 (Figure 5, Figure S-6, Figure S-8). There were few anthropogenic sound sources in this period, and no 3-D seismic surveys were conducted. The general shape of the spectra are similar to those reported from sonobuoy studies in 1981 (Leggat *et al.*, 1981). The 100–1000 Hz band, driven by wind action, has the highest sound levels during summer. During winter, ice cover reduced the sound levels above 100 Hz from December to May (Figure S-6, Figure S-8) (see also Roth *et al.*, 2012). Biologic sound sources were infrequent, with the exception of bearded seals (*Erignathus barbatus*) in May and June (Frouin-Mouy *et al.*, 2015).

The sound spectra recorded at Station BB4 in Melville Bay were consistent with glacial ice melt. The median 1-min SPL was 116 dB re 1 μ Pa, 14 dB higher than the 102 dB re 1 μ Pa at Station BB7 in summer 2013 (Figure 5, Figure S-5, Figure S-8). The highest Melville Bay sound levels were in the 1000–10000 band, whereas in the data from other stations the 1000–10000 Hz band were much lower than the 100–1000 Hz and 10–100 Hz bands. Listening to the sound files from Station BB4 (e.g., the data represented in Figure S-7) reveals many instances of ice cracking, as well as pops and hisses that are likely caused by air escaping from melting glacial ice (Pettit *et al.*, 2015). This is reasonable given that station is near the Greenland coast and its calving glaciers (Figure 1).

Figure 5: Comparison of the statistical received sound levels for the four sound scenarios in Fig. 4. From left to right the bands are 10–32000, 10–100, 100–1000, 1000–10000, and 10000–32000 Hz.

Seismic pulses were rarely detectable at Station BB4 (e.g., Figure 4), and the 1-min SPL was uncorrelated with the distance to the *Samur* and *Amani* (Figure 6, $r^2 = 0.017$, $SE = 0.31$). The periods with higher sound levels (e.g., 7–11 Sep, Figure 4) did not contain pulses originating from the seismic surveys in the adjacent lease areas either; instead, these periods contained more loud ice cracking events than the quieter periods.

Figure 6: Ranges from Station BB4 to the *Samur* and *Amani* in summer 2012 and the 1-min SPL.

The octave-band 1-min SPLs at Station BB6 in September 2013 (Figure S-8, Table S-5) were used to establish a threshold where the seismic survey sounds would stand out against the ambient background sounds and begin masking other sounds in the same band as the received seismic energy (see Section III.G). The data preceding the 2012 seismic survey were not used because the time period was quite short and the dynamic range of the 2012 ambient recordings was limited by the low sensitivity of the M8E-0dB hydrophones (see Table S-3).

Nature of seismic airgun pulses in Baffin Bay

The seismic pulses recorded in Baffin Bay showed very strong multipath arrivals for source-recorder ranges (or separations) of less than 40 km (Figure 7, Figure 8). The pattern of arrivals depended on the depth of the hydrophone, the water depth (770 m), and the range to the seismic vessel. At 100 m hydrophone depth (Figure 7), the pulses arrived in pairs, where the first one was the upward traveling reflection from the seabed and the second was the downward traveling surface reflection. As the range to the vessel increased, the time between the impulses in each pair decreased due to the reduced differences in path length. The number of pairs arriving at the hydrophone also increased with range. At the 400 m hydrophone (Figure 8), the path lengths between the bottom and surface reflections were the same; hence, the impulses were evenly spaced. Similar to the measurements at 100 m water depth, the number of impulses increased with the distance to the vessel. The additional impulses increased the 90% energy duration every time an additional propagation path became important (Figure 9). The duration decreased with range as the length of the propagation path shortened. At ~40 km from the source, the number of arrivals depended on many propagation variables (e.g., bathymetry, bottom scattering roughness, weather), and the pulse lengths ranged from 2 to 6 s (Figure 9).

Also at ~40 km from the source, the received signal at 100 m depth began to exhibit a frequency upswing pattern in the 0.5–1 s initial arrival in the time series. This pattern became the dominant spectral feature at ranges greater than 40 km. These sweeps were the result of the sound being refracted into a low-velocity sound channel (Figure S-3). Higher frequencies were refracted more steeply than the lower frequencies, resulting in a longer path length and thus later arrivals at higher frequencies. Upsweeps were faintly present at 200 m depth, but they were not detected at 400 m depth (Figure 8).

Figure 7: Shape of 3480 in³ seismic array pulses at progressively longer ranges from Station BB3 in 770 m water depth at the 100 m deep hydrophone. All figures show 5 s of data. (Left) Time-series waveforms, and (right) spectrograms (1 Hz resolution, 0.2 s of data per FFT, 0.19 s overlap between FFTs, Hamming window). The SPL and SEL are for the T90 window durations shown.

Figure 8: Shape of 3480 in³ seismic array pulses at progressively longer ranges from Station BB3 in 770 m water depth at the 400 m deep hydrophone. These are the same pulses as shown in Figure 3 at 100 m depth. All figures show 5 s of data. (Left) Time-series waveforms, and (right) spectrograms (1 Hz resolution, 0.2 s of data per FFT, 0.19 s overlap between FFTs, Hamming window). The SPL and SEL are for the T90 window durations shown.

Figure 9: The 90% energy pulse duration compared to range for the data received at Station BB1 and BB3's 100 m deep hydrophones. Data were selected from 3.7 days when only a single seismic vessel was active. Ranges to the vessels were 1–150 km. For each minute of seismic activity, the five pulses with the highest energy were selected and plotted.

The pulses recorded in Baffin Bay had a different character than those reported from other deep water measurements, in that the direct arrival and subsequent multipath arrivals in the recordings from Baffin Bay study had similar amplitudes (within 1–6 dB). These signal characteristics were sustained at ranges between 1 and 40 km, unlike those reported by Madsen *et al.* (2006) from deep waters in the Gulf of Mexico where the first arrival had much higher levels than the multipath arrivals. The pulse structure was also different than the long reverberant pulses observed at intermediate ranges in deep water in the Lau Basin by Bohnenstiehl *et al.* (2012b); however, the long range pulses (127 km) recorded at 400 m depth in Baffin Bay were similar to the Lau Basin pulses at comparable ranges (Figure 8).

The presence of many multipath arrivals in the present data suggests a smooth and flat seabed with a high reflection coefficient in the Baffin Bay project area. The Lau Basin region, by comparison, is a tectonic spreading zone with a very high sound speed bottom (primarily basalt with little surface sediment accumulation) that should be an excellent reflector. However, random seafloor deformations at the Lau Basin spreading zone scatter the higher frequencies so that only low frequencies propagate long distances in the Lau Basin. Bay. We note, by contrast to the deep water propagation conditions in Baffin Bay and the Lau Basin, that seismic pulses received in shallow water areas (<100 m) are affected by shallow water filtering (Urick, 1983), head waves from higher speed propagation in the substrate, and modal dispersion (Guerra *et al.*, 2011; Guan *et al.*, 2015).

Cumulative sound exposure and predictions of ranges to radii for auditory injury of marine mammals

As discussed in the Introduction, recent frameworks for assessing the effects of noise on marine life (e.g., Southall *et al.*, 2007; Popper *et al.*, 2014; MNFS 2016) use two criteria to assess the risk of auditory injury: peak sound pressure level and cumulative SEL. For airgun arrays, the peak sound pressure level drops below the injury threshold level for marine mammals at a range of tens of meters. The cumulative SEL drops below the suggested regulatory sound levels for injury at ranges of hundreds of meters and can be 1 km or longer and becomes the zone that is monitored for protection of marine mammals (e.g. Matthews, 2012). This is especially true for a stationary receptor. Thus, an analysis of the cumulative SEL metric using the Greenland data may be instructive for future regulatory discussions.

The radius around the source where the measurements suggest possible auditory injury to marine mammals depends on which set of thresholds and auditory weighting functions are used. The *Guidelines to Environmental Impact Assessment of Seismic Activities in Greenland Waters* (Kyhne *et al.*, 2011) mandates the M-weightings and thresholds recommended in Southall *et al.* (2007). In the intervening period between the project and present, new approaches have been distributed by the National Ocean and Atmosphere Administration (NOAA) for the United States. Each approach uses different auditory weighting methods and thresholds for auditory injury and behavioral disturbance. To estimate the ranges when the cumulative SEL exceeded the thresholds, we computed the frequency-weighted daily SEL at Stations BB1 and BB3 and plotted them against the closest point of approach of the seismic vessels for that day (Figure 10). The Southall *et al.* (2007) weighting functions and thresholds predict potential hearing damage for pinnipeds at ranges of 600 m from the vessel and that low-frequency cetaceans could be injured at very close ranges (<100 m, Figure 10). The NOAA Technical Guidance (NMFS 2016) weighting functions and thresholds predict that the acoustic energy from this survey could injure high-frequency cetaceans at ranges of less than 500 m (Figure 10). On eight days when the seismic vessels' closest points of approach to the stations were greater than 10 km, the measured exposure levels were exceeded the high-frequency cetacean threshold. Our review of these events showed that seismic sounds were present; however, additional energy from the close passage of other vessels (ranges and vessel identities are unknown) increased the sound levels in the high-frequency weighted cetacean SEL for those days. The NOAA Technical Guidance threshold for exposure of high-frequency cetaceans to non-impulsive sounds is 173 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$, and these exposures do not exceed the threshold. The data were included as 'seismic' by the automated processing since detection was performed on unweighted data and the weighting applied to the impulses after detection. These results highlight the continued need for research into the appropriate auditory weighting functions for marine species, the effects of sound on marine life, methods of data analysis, and thresholds that will minimize impacts.

Figure 10: Exceedance of frequency-weighted daily SELs compared to three injury metrics versus the closest range to either seismic vessel for the 100 m hydrophone at Station BB1. (Left) Southall *et al.* (2007) injury threshold. (Right) NOAA Technical Guidance (2016) permanent threshold shift (PTS). Positive values exceed the thresholds. Frequency band abbreviations: LF – low-frequency cetacean auditory weighting; MF – medium-frequency cetacean auditory weighting; HF – high-frequency cetacean auditory weighting; Pinniped – pinniped weighting from Southall *et al.* (2007) and the phocid weighting from NOAA Technical Guidance (2016). The light-gray shaded high-frequency data also contained significant levels of energy from the close passage of vessel and hence are comparable to the threshold of 173 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ rather than 155 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$, and hence do not constitute an exceedance of the thresholds.

Depth dependence of seismic pulse energy

DCE’s review of the possible effects of seismic surveys on marine life raised the question of variation in the received levels as a function of depth (Wisniewska *et al.*, 2014); therefore, our study recorded acoustic signals at 100, 200, and 400 m below the sea surface. We found that the SPL, per-pulse SEL, and 24-hour SEL showed only minor variations in the received sound levels as a function of depth in Baffin Bay. Figure 7 and Figure 8 show that the received sounds at ranges beyond 40 km from the source at a 100 m depth contained a low-frequency upsweep that was not present at 200 and 400 m depth, as described in the Section III.B. In the longest-range case (127 km), the SPL at 100 m depth was 6 dB higher than at 400 m; however, the pulse was also 4 times shorter at 100 m, which resulted in the same SEL at both depths.

At close ranges (0–3 km) there were differences with depth in the received signals that depended on the multipath reflections arriving at different times and the vertical beam pattern of the seismic array (Figure 11). Because the hydrophones were at different depths, the first reflection of the seismic pulse arrived at the 400 m hydrophone, followed by the 200 m and finally the 100 m hydrophone. This pattern was reversed for the subsequent surface reflection (Figure 11). Seismic arrays concentrate sound in the vertical direction with an angular beam width that depends on frequency (Figure S-9). As the vessel approached within 1 km of the recording station, the deepest hydrophone ‘entered’ the beam first, and therefore as the vessel approached the received sound level at 400 m depth rose before the levels at the 200 and 100 m depths (Figure 11). At the closest point of approach, all three hydrophones were almost entirely in the main lobe of the seismic array, so that the 100 m deep hydrophone had the highest sound levels since it was closest to the array and had the lowest geometric spreading loss.

Figure 11: Per-pulse SEL for 125 ms impulses detected at Station BB3 hydrophones from the 3480 in³ seismic source as it passed the station on 18 Sep 2012. Differences in received sound levels were primarily within the first 3 km from the source.

The daily SEL integrates the received exposure levels over a 24-hour period and provides a macroscopic assessment of the sound levels as a function of depth. The SELs were virtually identical at all depths, except when the source passed directly over the receivers. The single pulse SELs at the closest point of approach differed by 7 dB between the 100 and 400 m recordings (Figure 11), yet the daily SELs only differed by 2 dB (Figure 12). The frequency content at all depths was also virtually identical (not shown). We conclude that for the purposes of assessing the possibility of auditory injury or behavioral disturbance to marine mammals, the sound levels as a function of depth can be treated as uniform for the conditions in Baffin Bay.

Figure 12: Daily SEL at Station BB3 for the entire recording period at each hydrophone depth. Differences in SEL between depths were only measured before the seismic program started and when the source passed directly over the receivers. Stations BB1 and BB2 produced similar results.

Verification of propagation modeling results with actual environmental inputs

A knowledge gap identified during the pre-survey modeling effort (Wisniewska *et al.*, 2014) was the poor understanding of the dependence of acoustic propagation model results on the accuracy of the environmental inputs, since there was little high fidelity data available for Baffin Bay to base such an analysis on. The acoustic measurements collected as the seismic surveys passed Stations BB1 and BB3 enable us to directly compare the environmental parameters used for the pre-survey acoustic modeling (Matthews, 2012). The acoustic propagation model was re-run with the source at the vessel's closest point of approach to Station BB1 along the radial from BB1 to BB2 and BB3 (Figure 1). The measured per-pulse fixed window SPL as the ship approached Station BB1, as well as the simultaneous measurements at BB2 and BB3, were compared to the pre- and post-survey modeled SPLs. The SPLs were computed by applying a range-dependent conversion factor to the SELs modeled by MONM. The conversion factor was computed by running a full waveform version of MONM and computing the pulse duration as a function of range. The pre-survey modeled levels were 3–7 dB higher than the measured values at ranges greater than 500 m (Figure 13, left). Using the measured sound speed profile did not improve

the error significantly. The results were improved (Figure 13, right) by improving the correction factor. The full waveform model was re-run using the bathymetry measured by the seismic survey vessels along the line from Stations BB1 to BB3 and the measured sound speed profile (Figure S-10, Figure S-3). The pre-season conversion factor had been computed along two radials, one from Station BB1 east and the other west. By using the more accurate conversion factor, the error reduced to 0–4 dB, even 65 km from the source.

Figure 13: Comparison of the per pulse fixed window SPL Stations BB1 to BB3 on 4 Sep 2012 as the Amani passed over the hydrophones at BB1 with the modeled outputs (left) using the pre-survey sound-speed profile, bathymetry, and SEL-SPL conversion radials, and (right) using the measured sound-speed profile, bathymetry, and SEL-SPL conversion radial from BB1 to BB3.

Approaches for computing SPL

The first regulatory guidance for limiting effects of sound on marine mammals used the per-pulse SPL as the threshold metric for both behavioral disturbance and injury. Subsequent research has concluded that dual thresholds for the peak sound pressure level and weighted sound exposure levels are appropriate for limiting injury from sound (Southall *et al.* (2007), Popper *et al.* (2014), NMFS 2016), however no direction has emerged for behavioral disturbance. Madsen (2005) clearly articulates the issues with variable length windows when calculating an impulsive SPL. Here we provide results from the long-term and long-range Baffin Bay dataset that supports Madsen's assertion. We demonstrate that if SPL must be used, any fixed window duration is preferable to a variable length window (e.g. the 90% energy duration). We then show how this result supports Tougaard *et al.* (2015) argument that it is essential that the metric used to establish a regulatory threshold be the same one that is used to measure compliance.

Measuring the peak and average sound levels is inherent in any study of the response of marine life to sound stimuli. In addition to the behavioral state of animals, the wide variability within and between the responses of individual animals makes it difficult to understand what elements of the sound are eliciting a response. It may be the similarity of a sound to predator calls, frequency content, absolute level, duration, the onset of the sound, rise time, perceived distance to the source, perceived motion of the source, or other cues not yet discovered (Wartzok *et al.*, 2003; see reviews in NRC 2005; Nowacek *et al.*, 2007; Southall *et al.*, 2007; Gedamke

et al., 2011; Ellison *et al.*, 2012; Pirotta *et al.*, 2012; Risch *et al.*, 2012; Deruiter *et al.*, 2013; Goldbogen *et al.*, 2013; Popper *et al.*, 2014; Miller *et al.*, 2015). Early studies of the effects of impulsive sound on marine life measured the SPL over a time window that includes 90% of the pulse energy (Blackwell *et al.*, 2004; Thode *et al.*, 2010). Madsen (2005) and Madsen *et al.* (2006) advocate computing the SPL over a maximum window of 100–200 ms, the presumed integration time range of the hearing system for most mammals, including all marine mammals that have been tested.

We compared how the peak sound pressure level and the SPL changed as the seismic source approached the recorders. The SPL was computed three ways: with a 125 ms fixed window, a 1-min fixed window, and a variable window that included 90% of the pulse energy. The 125 ms window has been shown to be near the time span over which mammalian ears integrate sound, and it applies to both terrestrial and marine mammals (Plomp and Bouman, 1959; Johnson, 1968; Kastelein *et al.*, 2010). In particular, Tougaard *et al.* (2015) transpose measurements from 11 other studies to the signal level in a 125 ms ‘leaky integrator’ and demonstrate that the onset of disturbance using this integration time was 40–50 dB above the porpoise audiogram and closely followed the shape of the audiogram. We chose to use a fixed duration 125 ms fixed window since it is much easier to implement than the leaky integrator and has a maximum difference in calculated sound levels of 2 dB compared to the leaky integrator—a difference far smaller than the spread of SPL values associated with marine mammal disturbance (Tougaard *et al.*, 2015). The fixed window also has the advantage of estimating conservative sound levels for pulses with high initial amplitudes and long reverberant tails, such as those from seismic surveys and pile driving.

For this analysis, we choose 3.7 days of data from the 100 m deep hydrophones at Stations BB1 and BB3 during periods when only a single seismic vessel was active. Ranges to the vessels were 0.5–150 km. As expected, the results of all four methods of computing the SPL exhibited a common trend of increasing sound levels as a vessel approached a station (Figure 14). However, each of the metrics had different slopes as a function of range, and different degrees of variability in the instantaneous variance and the deflections of the smoothing curve. The variance of the individual measurements increased with decreasing integration time, but the smoothing curves had fewer deflections. With longer integration times, there was less variance in the individual measurements, but the smoothing curve showed larger deflections, providing better insight into the average change in propagation loss as function of range. The T_{90} SPL was closer to the 125 ms SPL at short ranges, and closer to the 1-min SPL at long ranges. We expect that the variability depends on range, water depth, bottom shape, and bottom type. Therefore, the relationship between the T_{90} SPL will be more dependent on the environment than the peak sound pressure levels, 125 ms SPL and 1-min SPL, which is undesirable for a regulatory metric.

Given the variable nature of the attenuations, the data were fit with an additive model (mgcv::gam; Wood, 2004), which smoothly followed the changing sound level attenuation as a function of range (e.g., Figure 14 and Figure 11). The additive models were fit with 6–20 knots (e.g., gam(SPL ~ s(range, k=20))). These models had much, much lower Akaike information

criterion scores than linear models of the form $(\text{SPL} \sim \log_{10}(\text{range}) + \text{range})$ and provided a much better representation of the data. We recommend the use of additive models for predicting sound exceedance isopleths for measurement programs where the attenuation changes with range (i.e., from spherical-like spreading to cylindrical-like spreading (Figure 11))

Additive models were generated for each averaging duration and used to compute the range where the peak SPL and SPL dropped below 120, 130, 140, 150, 160, 170, and 180 dB re 1 μPa (Table 2). The ranges to the isopleths were highly dependent on the integration times. For example, the 160-dB isopleth was 48 km for the 125 ms integration time, but 26.5 km using the 90-percent energy windows and 11.6 km for 1-minute integration. This result underscores the argument made in Tougaard *et al.* (2015) that measurements performed to assess compliance with a regulatory threshold must use the same metric that was used to establish that threshold. Regulatory directions and/or international standards should specify the signal analysis methods, as well as the thresholds to maximize consistency between localities and projects. Whenever possible the methods must be simple for regulators and project teams to implement. The 125 ms SPL is attractive for assessing seismic sources because 1) the duration is well matched to the length of the peak energy of the pulse in many environments; 2) it is near the length of time that the ears of many species groups integrates sound; 3) it is the fast-time weight duration in many sound level meters; and 4) it was shown by Tougaard et al (2015) to be a good predictor of the sound level at which porpoise respond to sound. We also note that the use of broadband SPL to predict behavioral reactions will likely be revisited. Like the weighted sound exposure levels used to estimate the onset of permanent threshold shift (PTS) and temporary threshold shift (TTS), we expect that audiogram-weighted SPL are better predictors of behavioral reactions.

Table 2: Radii (km) to SPL isopleths predicted by mgcv::gam additive models for the sound levels (e.g., Fig. 15) generated using 3.7 days of data from time periods when only one seismic array was active. <0.1 and >150 indicate that the result is outside the range where extrapolation is considered unreliable.

Isopleth SPL (dB re 1 μPa)	Peak sound pressure level	125 ms fixed window	T90 SPL	1-min SPL
180	1	<0.1	<0.1	<0.1
170	6	0.5	1.5	<0.1
160	13.8	6	3.4	<0.1
150	41.8	14.8	8.3	1.6
140	111.8	48.3	23.1	11
130	>150	>150	75.1	54.1
120	>150	>150	>150	>150

Figure 14: Analysis of the peak SPL and SPL computed using three different averaging durations as a function of range to the source vessel. 3.7 days of data from periods when only one ship was emitting are shown; the 100 m hydrophones were used in all cases.

Spectral content of the measured data

We need to understand the spectral content of seismic pulses propagating over long distances to inform studies on the potential for seismic surveys to disturb marine mammals that communicate at frequencies above 1 kHz or to mask their communications or foraging calls (Goold and Fish, 1998; Madsen *et al.*, 2006; Hermannsen *et al.*, 2015). The hydrophones at 100 m depth were sampled at 64 ksp/s; their data thus provide information on the spectral content of seismic pulses up to 30 kHz over ranges of 0.1–150 km from the seismic source. For this investigation, we used the same 3.7 days of data that were selected for the SPL investigation (Section III.F). The peak sound pressure level as well as the broadband SPL and SPL resolved in 11 octave bands were plotted against the range to the seismic array. We computed the SPL using the 1-min (Figure 15), 125 ms (Figure S-11), and 90% energy duration (Figure S-12) window to help illustrate the differences between these metrics.

Additive models for the peak sound pressure level, SPL, and SPL in the octave bands from 16–16000 Hz were generated and used to determine where the SPL exceeded the median noise in the same band measured in September 2013 by 20 dB (Table 3). Twenty decibels was chosen as a general critical ratio for detectability of signals in noise at lower frequency bands across species groups (Au and Hastings, 2008; Erbe, 2008; Gaspard *et al.*, 2012; Sills *et al.*, 2014; Sills *et*

al., 2015). Using the 1-min SPL as an indication of the continuous noise from the seismic survey in Greenland waters, the range was 80 km for the 125 Hz band and decreased to 5.7 km for the 16 kHz octave band (Table 3). It should be noted that the 16 kHz band integrated sound from 11 to 22 kHz; the large bandwidth increased the noise background compared to other bands, so that the noise floor of the recorder was reached at 6 km in this band (e.g., Figure 15). For the 16 kHz band, only up to 4 km was used to generate the additive models and predicted results would have been rejected if the range exceed 8 km. For all other bands with predicted ranges less than 150 km, the models were only interpolated and not extrapolated.

We carefully reviewed the data collection, data analysis, and sound propagation effects to verify that these high-frequency measurements were real. We conducted a detailed review of the signal analysis software and verified that the high-frequency components were not an artefact of spectral leakage in the Fourier transforms. Because the multipath features of the signals measured at 100 m and 400 m depth were very similar (Figure 7, Figure 8), we are confident that the frequency content is similar throughout the water column, at least to 40 km from the source. Beyond 40 km, the high-frequency content measured on the 100 m deep hydrophones may be unrepresentative of the full water column. The hard and flat bottom conditions that we believe are responsible for the distinct multipath arrivals of the seismic pulses in Baffin Bay are also responsible in part for the long ranges where higher frequencies are still present. As noted in Section II.C, the 100 m hydrophones were on the lower edge of the surface sound duct, so that the levels reported here are may be lower than would have been measured at 60 m.

Table 3. Range from the source (km) where the seismic pulse sound levels exceed the median one-minute SPL for Sept 2013 at station BB6 by 20 dB (Table S-5¹). The range was limited to 150 km to avoid extrapolating beyond the measured data.

	Averaging duration		
	0.125-s SPL	90% energy duration SPL	1-min SPL
Peak SPL	89.3	91.8	97.9
SPL	>150	>150	>150
Octave bands:			
16 Hz	>150	>150	>150
31 Hz	>150	>150	>150
63 Hz	>150	>150	>150
125 Hz	145.5	117.3	77.9
250 Hz	102	56.6	44.7
500 Hz	86.8	41.4	32.5
1 kHz	21	27.5	17.4
2 kHz	17.5	21.5	13.5
4 kHz	16.4	16.9	10.6
8 kHz	12.4	11.6	9.4
16 kHz	6.1	6.8	5.7

¹ See supplementary material at <https://doi.org/10.1121/1.5014049> for the additional figures and tables referenced in this chapter.

Figure 15: Received 1-min peak sound pressure level, broadband SPL, and octave band SPLs (all in dB re 1 μ Pa) for ranges of 0.5–150 km during the 2012 Greenland survey. The 5400 min of data shown are from periods when only one seismic survey source was emitting; the 100 m hydrophones at Stations BB1 and BB3 were used in all cases. To record the high seismic sound levels without saturating the hydrophone, low sensitivity hydrophones were employed. The system spectral noise floor was 58–63 dB re 1 μ Pa²/Hz, or 98–103 dB re 1 μ Pa broadband in the 16 kHz octave band (see Table S-3). The median ambient 16 kHz octave SPL in September 2013 was 77.9 dB re 1 μ Pa (Table S-5).

Summary and Conclusion

The Baffin Bay recordings of seismic airgun and ambient sound levels in 600–770 m water depth were analyzed to understand the effects of a 3-D seismic survey on the acoustic environment. In 2012, data were recorded at three stations using vertical arrays with three hydrophones each; the top hydrophone at 100 m depth sampled at 64 ksp/s. A follow-on measurement of a shallow-hazards seismic program in 2013 and a year-long recording program overwinter in 2013–2014 showed that the soundscape in Baffin Bay is typical of open-ocean with little anthropogenic noise. The August to September soundscape closer to shore in the Melville Bay nature sanctuary is loud and dominated by the sounds of melting glacial ice.

The seismic airgun sounds measured within 40 km of the source included up to 20 distinct multipath arrivals, far more than has been reported for seismic surveys in other deep water environments. The pre-survey estimates of received sound levels were 3–7 dB higher than the levels measured for ranges of 0.5–65 km. The error between the measured and modelled sound levels decreased to 0–4 dB by using the sound speed profile, bathymetry, and modeling along the same radial as was measured.

When the vessel was closer to a station than 40 km, there was virtually no difference in the daily SEL as a function of depth; however, there were short-term variations in per-pulse SEL and SPL on the order of 6 dB. At ranges of 40 km from the seismic source, the difference in levels as a function of depth became significant. At 40 km, the SPL was generally below 140 dB re 1 μ Pa, which is well below the levels associated with risk of injury to marine life. In the project area, the sound speed profile below 400 m is either iso-velocity or downward refracting. Thus, measuring at the seabed would have provided similar information within 40 km of the source as we measured with the vertical arrays. For future monitoring projects in similar environments, we recommend collecting data at the seafloor only (assuming a downward refracting sound speed profile), which will allow for simpler moorings that are lower cost and easier to deploy and retrieve. These types of moorings have the added advantage of exhibiting lower levels of flow induced pseudo-noise since most locations have little current at the seafloor.

The measured sound levels were compared to several proposed regulatory thresholds for auditory injury. Using the frequency weighting functions and thresholds recommended in Southall *et al.* (2007), which were incorporated into the *Guidelines to Environmental Impact Assessment of Seismic Activities in Greenland Waters*, we estimated the threshold of injury for low-frequency cetaceans at a range of <100 m and for phocids (seals) at a range of 600 m. These ranges agreed with the maximum expected ranges from the pre-survey modeling.

We noted that the SPL is a difficult metric to employ for regulatory thresholds, however, it remains in use for many purposes and demonstrated how the SPL depends on the integration time. We compared the SPL computed using two fixed window durations (125 ms and 1 min) with the SPL computed using 90% energy duration of the seismic pulses. The sound levels did not smoothly decrease as a function of range with any of the metrics and were best described using an additive model rather than a linear regression. We found that the integration time affects what information we extract from the data. Unsurprisingly, shorter integration times provide better information on the instantaneous variance in the signal, while longer integration times smooth the variance and reveal longer-term effects. The peak sound pressure level, 125 ms SPL, and 1-min SPL curves tracked each other while the T_{90} SPL was closer to the 125 ms SPL at short range and close to the 1-min SPL at long range. Thus, the T_{90} SPL depends on the environment more strongly than the fixed integration windows and is not recommended for establishing regulatory thresholds. If the SPL must be used for characterizing the effects of sound on marine life, we suggest standardizing on the 125 ms window for seismic sources.

The Baffin Bay recordings confirm previous reports that seismic airgun sounds include energy up to at least 30 kHz. The SPL in the band used by dolphin species for social whistle communications (16 kHz octave band) were increased by 20 dB compared to the ambient levels measured in September 2013 at ranges of 6 km from the source vessels for all integration durations.

The collection and analysis of this dataset has produced a wealth of new information on the Baffin Bay environment and the variability of seismic array sound propagation. This study shows the importance of collecting systematic data during industrial operations when there are

uncertainties in the possible effects of the activity on the acoustic environment. Future projects can extend this work by verifying the dependence of the multipath arrivals and high-frequency content on the bottom composition and depth, investigating the azimuthal characteristics of a seismic array, exploring the variation in sound levels with depth in different environments, and attempting to measure the behavioral reactions of marine life as a function of range to the seismic source.

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Chapter 7

Seasonal trends in acoustic detection
of marine mammals in Baffin Bay and
Melville Bay, northwest Greenland

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Abstract

The expansion of hydrocarbon exploration in northwest Greenland has made it increasingly important to understand the occurrence of marine mammals in the region. Here the seasonal and spatial call occurrence of marine mammals in Baffin Bay and Melville Bay are described. Four Autonomous Multichannel Acoustic Recorders (AMARs) were deployed during summer 2012 (late July to early October), five recorders during September 2013, and two recorders were deployed year-round in 2013–2014 (late September 2013 to early September 2014). Species' call presence was analysed using automatic call detection and manual verification analysis methods. A novel approach, described in this article, to discern narwhal (*Monodon monoceros*) clicks from beluga (*Delphinapterus leucas*) clicks was implemented during the verification process. Narwhal calls were detected in spring and fall, showing a south-north migration pattern in spring and a north-south migration pattern in fall. Few beluga whales were detected during fall 2013 and spring 2014. Bearded seal (*Erignathus barbatus*) calls were detected mainly during spring (mating period). A small number of bowhead whale calls (*Balaena mysticetus*) were detected during fall 2013 and spring and summer 2014. For the first time at this latitude in the western Arctic Ocean, long-finned pilot whales (*Globicephala melas*) and sperm whales (*Physeter macrocephalus*) were detected during summer and fall. Our results suggest that the presence of marine mammals in Baffin Bay and Melville Bay is mainly governed by the annual cycle of sea ice formation and decay.

Keywords: Northwest Greenland, Baffin Bay, Melville Bay, passive acoustic monitoring, sperm whales, narwhals, long-finned pilot whales, bearded seals, bowhead whales, beluga whales, narwhal clicks, beluga clicks.

Introduction

The waters of Baffin Bay and Melville Bay off West Greenland are some of the most productive and tightly connected physical-biological systems in the marine environment (Laidre *et al.* 2010). The region is ice covered in the winter and thus far has had limited vessel traffic resulting in a local soundscape dominated by icebergs, sea ice, wind, waves, and wildlife sounds. However, human activities are increasing in these waters. In 2010, five petroleum exploration licence blocks were awarded in Baffin Bay (Fig 1), and the potential opening of the Northwest Passage could lead to regular vessel transits in this area. Vessels associated with transportation and oil and gas exploration and production have the potential to change the soundscape and impact local species, particularly marine mammals (Heide-Jørgensen *et al.* 2013b). Marine mammals depend on sounds for many critical life processes including navigating, communicating, monitoring young, mating-related and social displays, and foraging (Tyack and Clark 2000). Such crucial activities can be negatively impacted by the masking effects of anthropogenic noise, leading to reduced fitness and/or loss of usable habitat (Bejder *et al.* 2006).

A number of marine mammals including narwhals (*Monodon monoceros*), beluga whales (*Delphinapterus leucas*), bowhead whales (*Balaena mysticetus*), and bearded seals (*Erignathus barbatus*) are known to occur in Baffin Bay off West Greenland (Dietz and Heide-Jørgensen 1995; Doidge and Finley 1993; Finley and Renaud 1980; Stafford *et al.* 2012b; Stafford *et al.* 2008). The spring bloom of primary productivity triggered by retreating sea ice attracts high densities of prey species in the lower trophic level, including forage fish and zooplankton that many marine mammal species follow into the region. (Heide-Jørgensen *et al.* 2013a; Laidre *et al.* 2010). Little is known about the year-round occurrence of marine mammals, particularly in winter when environmental conditions make traditional monitoring methods challenging. Thus far, research in the region has been limited to visual surveys, which can take place only from spring to late fall (Finley and Renaud 1980; Heide-Jørgensen *et al.* 2013a), and studies using satellite transmitters on a few individuals from a population (Dietz and Heide-Jørgensen 1995; Heide-Jørgensen *et al.* 2003a; Heide-Jørgensen *et al.* 2006; Teilmann *et al.* 1999). More detailed information on marine mammal occurrence in and around Baffin Bay, south of the North Water Polynya, is required to adequately manage the risks to marine mammals associated with offshore oil and gas exploration.

Passive acoustic monitoring using multiple recorders is a reliable method for measuring temporal and spatial distributions of sound-producing marine mammals for long periods over large areas, as well as in remote locations and during weather conditions or seasons that would otherwise prohibit direct observation (e.g., Hannay *et al.* 2013). Acoustic detection and classification of marine mammal calls requires that animals produce sounds that 1) have sufficient amplitude to be detected in the presence of other sounds and 2) are species-unique to allow confident species identification. Thus, the results obtained from acoustic studies apply only to acoustically active animals producing relatively unique calls within a given distance from the recorders. Species with high vocalization rates and long calling bouts (e.g., bearded seals) are

more likely to be recorded incidentally compared to species with lower vocalization rates, short calling bouts or whose calls do not propagate as far (e.g., beluga whales). Sounds below 1 kHz (typical of mysticete calls) have significantly less seawater absorption loss than sounds above 10 kHz (typical of odontocete calls), and thus can be detected at greater distances (Mellinger *et al.* 2004b). Mysticete calls are commonly detected at ranges of several tens of kilometres on a single hydrophone (Stafford *et al.* 2007), while odontocete clicks and whistles can be detected at ranges of 1–6 km (Ainslie 2013; Jensen *et al.* 2012; Quintana-Rizzo *et al.* 2006; Wang *et al.* 2006).

Stafford *et al.* (2012a) and Marcoux *et al.* (2012) discuss the large overlap in vocal repertoires of the two monodontidae species (beluga whales and narwhals) that share migration routes in Baffin Bay (Heide-Jørgensen *et al.* 2003a; Heide-Jørgensen *et al.* 2003c). To our knowledge, no studies have systematically discriminated between calls of these species. Their repertoires have been explored independently, often focusing on tonal calls (Belikov and Bel'kovich 2006; Ford and Fisher 1978). While such information is useful, narwhals and especially beluga whales have large vocal repertoires that are only partially described, resulting in a potential interspecies call overlap and low identification reliability (Sjare and Smith 1986). Both species are ranked as near threatened by the International Union for Conservation of Nature and of special concern by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2004a; 2004b). Therefore, it is particularly important to be able to reliably acoustically discriminate between the monodontidae whales to allow for accurate monitoring of species-specific distribution and habitat use.

Most of the West Greenland marine mammal acoustic data published to date are recordings from Disko Bay or central Baffin Bay in spring (Stafford *et al.* 2008; Tervo *et al.* 2009) and winter (Rasmussen *et al.* 2015; Stafford *et al.* 2012a; Tervo *et al.* 2011; Tervo *et al.* 2009) and Inglefield Bay in summer (Miller *et al.* 1995). Here we present results of recordings of marine mammal calls in the Greenlandic waters of Baffin Bay at four locations from late July to September 2012 (including one recorder in Melville Bay), five locations in September 2013, and two locations from September 2013 to September 2014. We examine the acoustic presence of several marine mammal species and describe a method to differentiate narwhal clicks from beluga whale clicks when repertoires overlap. We investigate whether there is an association between marine mammal detections and ice presence.

Material and Methods

Deployments

Between 29 July and 2 October 2012, we deployed Autonomous Multichannel Acoustic Recorders (AMARs, JASCO Applied Sciences) at stations BB1–BB4 (Figure 1 and Table 1). Each AMAR was fitted with a GTI-M8H current-loop hydrophone (GeoSpectrum Technologies Inc.; –199 dB re 1 V/ μ Pa nominal sensitivity) with no gain applied. Stations BB1–BB3 were vertical arrays, with hydrophones at depths of 100, 200, and 400 m from the surface. The top

hydrophone (100 m depth) sampled continuously at 64 kilo-samples per second (ksps) to record both seismic airgun pulses and marine mammal calls. The two lower hydrophones (200 and 400 m depth) sampled continuously at 8 ksps, primarily to record seismic airgun pulses. The usable bandwidth was 10 Hz to 30 kHz for the top hydrophone and 10–3750 Hz for the lower hydrophones (the maximum frequency was limited by the anti-aliasing filter in the analog-to-digital converter to be 0.47 of the sampling rate). At station BB4, located within Melville Bay, we deployed an AMAR at the sea bed (370 m) with a single omnidirectional GTI-M8E hydrophone (–165 dB re 1 V/ μ Pa nominal sensitivity) sampling at 64 ksps, resulting in a usable bandwidth of 10 Hz to 30 kHz.

Between 31 August and 30 September 2013, we deployed AMARs at stations BB5–BB9 (Figure 1 and Table 1). The systems recorded continuously for 513 s at 64 ksps followed by 43 s at 375 ksps. Each AMAR was fitted with a single omnidirectional GTI-M8E hydrophone (GeoSpectrum Technologies Inc.; –165 dB re 1 V/ μ Pa nominal sensitivity) with no gain applied, positioned at mid-water column depth. The spectral noise floor was 23 dB re 1 μ Pa²/Hz for the 64 ksps recording channel and 30 dB re 1 μ Pa²/Hz for the 375 ksps recording channel. Both recording channels could measure a maximum sound pressure level (SPL) of 171 dB re 1 μ Pa.

Between 29 September 2013 and 6 September 2014, we deployed AMARs at stations BB10 (south; 1000 m water depth, 550 m recorder depth) and BB6 (north; 575 m water depth, 302 m recorder depth) (Figure 1 and Table 1). Each AMAR was fitted with an M8E-V35 dB omnidirectional hydrophone (GeoSpectrum Technologies Inc.; –164 dB re 1 V/ μ Pa sensitivity). The AMARs sampled on a 30-min duty cycle: 340 s at 64 ksps, then 43 s at 375 ksps, and then 1418 s of sleep. The 64 ksps recording channel had a spectral noise floor of 23 dB re 1 μ Pa²/Hz and could measure a maximum SPL of 171 dB re 1 μ Pa. The 375 ksps data were recorded with a spectral noise floor of 30 dB re 1 μ Pa²/Hz and a maximum SPL of 171 dB re 1 μ Pa.

Figure 1: Map of recording station locations for deployments in Baffin Bay for summer 2012 (green circles: BB1–BB4), summer 2013 (orange circles: BB5–BB9), and overwinter 2013–2014 (black triangles: BB6 and BB10). Inset shows approximate summer (red) and winter (green; northern overwintering ground: NWG and southern overwintering ground: SWG) distribution of narwhal subpopulation summering in West Greenland and overwintering in Baffin Bay, Davis Strait, or Disko Bay (data from Laidre and Heide-Jørgensen (2005a,b). Mean extents of polynya in April and June were issued from Dunbar (1969).

Table 1: Recorder deployment details for acoustic monitoring programs in Baffin Bay in summer 2012, summer 2013, and overwinter 2013 – 14.

Recording period and station	Location	Recording period (MM/DD/YY)	Hydrophone depth (m)
Summer 2012			
BB1	74.16N 61.98W	07/29/12 to 09/29/12	100, 200, 400
BB2	74.23N 61.85W	07/29/12 to 10/01/12	100, 200, 400
BB3	74.70N 61.01W	07/30/12 to 10/02/12	100, 200, 400
BB4	75.31N 58.64W	08/14/12 to 09/15/12	370
Summer 2013			
BB5	73.05N 62.10W	09/01/13 to 09/30/13	450
BB6	74.01N 60.74W	09/01/13 to 09/30/13	272
BB7	74.54N 61.04W	09/01/13 to 09/29/13	365
BB8	75.01N 60.50W	08/31/13 to 09/29/13	350
BB9	75.11N 60.36W	08/31/13 to 09/29/13	400
Overwinter 2013–2014			
BB6	74.01N 60.74W	09/29/13 to 09/06/14	302
BB10	73.05N 60.10W	09/30/13 to 08/19/14	550

Marine Mammal Visual Observations

We supplemented the passive acoustic detections of marine mammals with visual observations by marine mammal observers during the geophysical surveys in the summers of 2012 and 2013. Commencing on 16 July 2012 and 1 August 2013, marine mammal observers on the survey and support vessels surveyed animals during the transit from Nuuk, Greenland to the prospect area. During the survey period, animal observations were recorded as the support vessel made various transits to Upernavik and Nuuk. In 2012, the last observations were carried out on 16 October during transit to port. In 2013, while actual site survey activities ended on 17 October 2013, as per Mineral Licence and Safety Authority guidelines, the vessel was used as much as possible for marine life surveying by marine mammal observers. The last observations were carried out on 20 October 2013 during transit to port.

Marine Mammal Acoustic Detection

Automated Detection and Classification: Clicks from beluga whales (Figure 2), narwhals (Figure 2), and sperm whales (*Physeter microcephalus*; Figure 3A) were automatically detected and classified using JASCO's custom acoustic analysis software that identifies the oscillation of a click across the signal's normal level, a process known as a zero-crossing. The detector/classifier removed energy below 8 kHz, created a 0.5 ms root-mean-square (rms) time series, and identified potential clicks with a Teager-Kaiser energy detector. The time window of each click was then defined and used to compute three classification features: the number of zero crossings, the median time between zero crossings, and the slope of the change in time between zero crossings. The extracted features were then compared to a template for each species using the Mahalanobis distance. Each click was classified as the species with the lowest Mahalanobis distance within specified thresholds. The templates were determined by selecting ~ 100 high

signal-to-noise examples of each species' click, measuring the feature values for those clicks, and computing their covariance matrix.

Calls from bearded seals (Figure 3B) and bowhead whales (Figure 3C) were detected using JASCO's custom acoustic analysis software. The software identified call energy in the time-frequency domain. Contours were created by joining adjacent time-frequency bins that met specific threshold criteria before implementing a contour-following algorithm comparable to that of Nosal (2008). The contours were then assigned to a species if they were within specified parameters.

Automated detections were not carried out for long-finned pilot whale (*Globicephala melas*) calls (Figure 3D). There was no species-unique click template due to a lack of truth data (high resolution recordings with confident confirmation of species identification). It is important to note that acoustic analysis based on automatic detectors alone (without manual verification) is not reliable for some species, including long-finned pilot whales, in noisy environment conditions (faint calls). Long-finned pilot whales produce typical delphinid sounds, such as clicks, buzzes, and a variety of pulsed calls including whistles similar to those of narwhals and beluga whales (Nemiroff and Whitehead 2009; Weilgart and Whitehead 1990). In this study, long-finned pilot whale-like calls were refuted/accepted based on expert opinions on the whistles and time of year, as this species does not occur in ice-covered areas (Nemiroff and Whitehead 2009).

Manual Validation of Automated Detections: Our marine mammal results are displayed as the presence of each species over time. Since most automated marine mammal detectors generate a small number of false alarms, we determined a threshold number of calls per species per unit of time that maximised the true positive detections while minimizing the false detections. Files for analysis were selected from the 64 ksp/s 2012 summer data (30 min/file), the 375 ksp/s 2013 summer data (43 s/file), and the 375 ksp/s 2013–2014 overwinter data (43 s/file). By analysing the highest broadband files available for each recording (64 and 375 ksp/s), we were able to observe a greater range of calls types (e.g., clicks and whistles) allowing for greater accuracy when classifying calls to different species. For each recorder, 20 files per species detected were manually reviewed. Files were selected to represent a spectrum of automated detector results relative to the six species detected: ten files with high numbers of detections, five with moderate detections, and five with low detections. Files were selected throughout recording periods, and files within 3 h of each other were avoided. To identify when the detector missed calls (false negatives), the presence/absence of all species was logged in every reviewed file. Vessel and ice presence was also logged for all files.

Some Arctic species create sufficiently unique calls to allow for relatively easy and confident identification during manual analysis. Bowhead whales were identified by their moans, which typically range between 100–400 Hz and last about 1 s (Clark and Johnson 1984). Bearded seals were identified by their characteristic trills (Risch *et al.* 2007). Sperm whales were identified by their clicks, which occur at a slower pace and lower frequency than other odontocete clicks (Goold and Jones 1995).

Figure 2: The frequency spectra, time series graphs, and histograms for a narwhal (NW) click train (top) and a beluga whale (WW) click train (bottom) recorded where species identification was confirmed in West Greenland on 24 October 2014 and the Gulf of St. Lawrence on 8 July 2014, respectively (Table 2). Corresponding clicks across graphs are labelled appropriately and the vertical lines in all pressure/frequency graphs indicate a frequency of 15849 Hz (in black) and 19953 Hz (in red) (512 Hz frequency resolution, 0.266 ms time window, 0.02 ms time step, Hamming window).

Delphinoidea, especially closely related species, are challenging to acoustically distinguish from one another, and few studies have directly explored interspecific variation (Baron *et al.* 2008; Gannier *et al.* 2010; Miller *et al.* 1995; Rendell *et al.* 1999; Steiner 1981). Such is the case for the phonetically similar long-finned pilot whales, narwhals, and beluga whales that inhabit Arctic waters. To discriminate between such species during manual analysis, we focussed on calls known to be species-unique. Long-finned pilot whales were identified by their repeated pulsed calls (Nemiroff and Whitehead 2009) and the time of year of the calls, as they are not known to occur in ice-covered areas. Distinguishing narwhal calls from beluga calls was more challenging, as they both occur in ice-covered areas.

Narwhal and Beluga Calls – A Novel Approach to Click Differentiation: Occasionally, species-unique calls allowed us to easily differentiate between the two monodontidae species. Narwhals could be identified when nasally whistles and buzzes were paired with low frequency clicks near 19 kHz (Miller *et al.* 1995), 2–10 kHz, and/or 7–14 kHz (Stafford *et al.* 2012a). Beluga whales could be identified when bird-like whistles were paired with high-frequency clicks, peaking at up to 100–120 kHz (Au *et al.* 1985). However, in many instances during the ice-covered winter months, recordings contained only clicks centred at 30–60 kHz, a click type consistently observed in both narwhals and beluga whales (Au *et al.* 1985; Miller *et al.* 1995; Rasmussen *et al.* 2015; Roy *et al.* 2010; Stafford *et al.* 2012a).

To address this area of uncertainty, click trains from known recordings of narwhals and beluga whales were analysed in detail (Table 2). Recordings obtained from several studies in West and East Greenland containing narwhal clicks were analysed. West Greenland data include: 1) JASCO's recordings with sufficient narwhal whistles for positive identification and 2) recordings collected with a 96 kps dipping hydrophone by Kate Stafford and Kristin Laidre (University of Washington) that contained positively identified narwhal. Susanna Blackwell (Greeneridge Sciences, Inc.) and the Greenland Institute of Natural Resources provided a recording of a narwhal click train from East Greenland recorded with a 155 kps Acousonde tag attached to an animal not responsible for the clicks. Beluga whale clicks from the Gulf of St. Lawrence and the Chukchi Sea were also analysed. Recordings from these studies were collected by JASCO at 128 and 375 kps, respectively. A total of 17 narwhal and 20 beluga whale click trains were analysed, resulting in 186 and 162 clicks per species, respectively (Table 2).

Narwhal clicks substantially increased in 1/3-octave band sound pressure level (SPL) between the 15849 Hz and 19953 Hz bands, a feature consistently lacking in beluga clicks (Figure 2). A single exception was found in a narwhal click train from East Greenland in the Acousonde tag data, where all clicks peaked, rather than increased, in SPL in the 19953 Hz third-octave band. Regardless, the mean SPL change between the 15849 Hz and 19953 Hz third octave bands (dB re 1 μ Pa) was found to be significantly greater for narwhal (10.4 dB re 1 μ Pa) than for beluga (0.9 dB re 1 μ Pa) whale clicks (Figure 4; non-parametric Kruskal-Wallis test; chi-squared = 211, df = 1, *P*-value < 0.001). Therefore, to distinguish narwhals from beluga whales when analysing clicks within the 30–60 kHz range during manual analysis, the per-click

1/3-octave-band SPL were analysed. If the SPL of all clicks within a click train increased greatly (at least by 5 dB re 1 μ Pa) or peaked in the same band, calls were identified as narwhals. If the pressure was low at the 19953 Hz band relative to the rest of the click, calls were identified as beluga whales.

Figure 3: A) Spectrogram of sperm whale clicks recorded at station BB4 on 24 September 2013 (UTC) (256 Hz frequency resolution, 5.46 ms time window, 2.73 ms time step, Hamming window). B) Spectrogram of bearded seal downsweeps recorded at station BB10 on 23 April 2014 (UTC) (2 Hz frequency resolution, 128 ms time window, 32 ms time step, Hamming window). C) Spectrogram of bowhead downsweeping calls recorded at station BB10 on 25 October 2013 (UTC) (2 Hz frequency resolution, 12.8 ms time window, 3.20 ms time step, Hamming window). D) Spectrogram of long-finned pilot whale clicks (and whistles) recorded at station BB10 on 30 September 2013 (UTC) (2 Hz frequency resolution, 12.8 ms time window, 3.2 ms time step, Hamming window).

Table 2: Number of narwhal and beluga whale click trains and individual clicks analyzed from different regions.

Recording supplier	Recorder type	Region	Click trains	Clicks
Narwhal				
JASCO	AMAR	West Greenland	13	125
Laidre and Stafford	Dipping Hydrophone	West Greenland	3	25
Blackwell	Acousonde tag	East Greenland	1	36
Beluga				
JASCO	AMAR	Gulf of St. Lawrence	9	59
JASCO	AMAR	Chukchi Sea	11	103

Automated Detector Accuracy: A total of over 280 h of recordings were manually validated to determine the accuracy of autodetectors at identifying the occurrence of marine mammals in Baffin Bay in the period from 2012 to 2014. To define the minimum number of automated calls per unit time that accurately represented species presence, we used a maximum likelihood estimator to compare the validated manual analysis and the automated results. The algorithm maximised the detection probability, while minimizing the number of false detections using the ‘F-score’ (Powers 2011):

$$F = \frac{(1 + \beta^2)P * R}{(\beta^2)P + R}; P = \frac{TP}{TP + FP}; R = \frac{TP}{TP + FN}$$

where true positive (TP) is the number of correct detections, false positive (FP) is the number of inaccurate detections, and false negative (FN) is the number of missed detections. Precision (P) is the proportion of automated detections that are accurate, and Recall (R) is the proportion of calls that are auto-detected (Davis and Goadrich 2006; Roch *et al.* 2011). To put a greater emphasis on precision than on recall, $\beta = 0.5$ was used.

For the 2012 summer recordings, over 100 h (203 30 min-files) were manually analysed from the 64 ksp data set: 42 h from station BB1, 28 h from BB2, 14 h from BB3, and 16 h from BB4. The automated classifier was found to be ineffective for the 2012 summer acoustic data. Most recorders were inundated with vessel and seismic activity sounds and ice sounds dominated on station BB4, creating false automated detections. Despite the presence of seismic and vessel sounds, sperm whales and narwhals were detected during manual analysis.

Of the 2013 summer 375 ksp recordings, 2.8 h (231 43 s-files) were manually analysed: 30 min from station BB5, 34 min from BB6, 36 min from BB7, 40 min from BB8, and 26 min from BB9. Sounds from vessels and a shallow hazard surveying using a small seismic array (140 in³) were detected occasionally, particularly at stations BB7–BB9. Long-finned pilot whales, sperm whales, and narwhals were also detected during manual analysis. The comparison of manual analysis present/absent results to the automated detector count results revealed that a minimum of 50 narwhal and 211 sperm whale detections per file were required for the detector results to be accepted as true for each species and considered present within the file. These parameters were applied to the 2013 summer detector results, giving narwhal and sperm whale detections a precision of 0.91 and 0.78, respectively (Table S1).

In the 2013–2014 overwinter 375 ksp data, 3.6 h (299 43 s-files) were manually reviewed: 1.8 h from station BB10 and 1.8 h from BB6. Bowhead whales, sperm whales, long-finned pilot whales, narwhals, beluga whales, and bearded seals were detected. Vessel sound was rare at these stations, but ice sound occurred consistently from late November to late March at station BB10 and from the late of November to late April at station BB6. The comparison of manual analysis results to automated detector results revealed that a minimum of 3 narwhal, 7 sperm whale, 97 beluga whale, and 4 bearded seal detections were required per file for the species to be considered present at that time. These parameters were applied to the 2013–2014 overwinter detector results giving narwhal, sperm whale, beluga whale, and bearded seal detections a precision of 0.94, 0.88,

0.5, and 1, respectively (Table S2). Bowhead automated detections were unreliable, as they were often triggered by ice and/or other cetaceans; therefore, results presented here are only those that were manually verified.

Figure 4: Mean pressure change between 15849 Hz and 19953 Hz one-third octave bands (dB re 1µPa) of narwhal clicks (n = 186) and beluga clicks (n = 162) with 95% confidence intervals.

Sea Ice Data

Sea ice concentration data were obtained at a 10-km resolution from the Ocean and Sea Ice Satellite Application Facility (<http://www.osi-saf.org>). Daily sea ice concentrations were calculated from the closest measurement pixel to each recorder. The locations of sea ice edges were obtained from satellite imagery (NOAA National Ice Center, Washington, DC, <http://www.natice.noaa.gov/products/>).

The effect of the presence of ice on the occurrence of marine mammal calls was evaluated using a binary generalised linear model in the R software package (version 3.2.2; R Development Core Team 2010). We used Wald's tests to assess significance.

Results

Results of visual observations are presented here to support the acoustic findings. In summer 2012, marine mammal observers made a total of 857 observations of marine mammals in the license areas, representing 1428 individuals. In summer 2013, a total of 58 visual observations of marine mammal species representing 342 individuals were documented in the license areas (Figure 1). The number of sightings in 2013 was lower due to the significantly reduced project

scope and fewer vessels and thus observers. Several marine mammal species, including sperm whales and long-finned pilot whales, were visually observed from mid-July to mid-October 2012 (Figure 5A) and from early August to mid-October 2013 (Figure 5C). Bearded seals, ringed seals (*Phoca hispida*), harp seals (*Pagophilus groenlandicus*), hooded seals (*Cystophora cristata*), and harbor seals (*Phoca vitulina*) were observed in the vicinity of the stations (Figure 5B and 5D).

Narwhal clicks were detected during summer 2012 and September 2013 (Figure 6). The percentage of days/month with detected narwhal clicks was higher at the northern (inshore) stations (BB4 in August and September 2012; BB8 and BB9 in September 2013) than at other stations with detected narwhal clicks (BB3 in August 2012; BB5 and BB6 in September 2013). In 2013, the ice concentration in Baffin Bay (Figure 7) increased in late October (station BB6) and early November (station BB10). The study area was fully ice-covered from early December 2013 until early June 2014. During fall (late September to late December) 2013, narwhal clicks were detected at the southern station (BB10) on 25 days and at the southeastern station (BB6) on 15 days (Figure 7). Narwhals were detected at the southern station (BB10) on 55 days and at the southeastern station (BB6) on 72 days during spring (March to late June) 2014 (Figure 7). The probability of occurrence of calls (Figure 8) increased significantly with ice concentration for narwhals (Wald's test: $\chi^2 = 25.5$, $p < 0.001$).

Beluga whale clicks (Figure 7) were detected at both southeastern (BB6) and southern (BB10) stations before the ice formation (October to early November 2013), during the ice formation (mid-November 2013), and in spring 2014 when the area was still ice covered (more than 90% of ice concentration).

Bearded seal calls were manually identified at the southeastern station (BB6) on 1 day during winter 2013–2014 (Figure 7). Bearded seal calls were also detected on several days during spring 2014 and peaked from early May to mid-June at both southeastern (BB6) and southern (BB10) stations (Figure 6). The probability of occurrence of calls (Figure 8) increased significantly with ice concentration for bearded seals (Wald's test: $\chi^2 = 73.6$, $p < 0.001$).

Bowhead whales were identified during manual validation analysis at the southern station (BB10) on 4 days in fall 2013 and spring 2014 and at the southeastern station (BB6) on 2 days in spring/summer 2014 (Figure 7).

Long-finned pilot whales were manually identified on several occasions in summer 2013 at the offshore stations (BB5 and BB6) (Figure 6). They were manually detected at the southern station (BB10) during winter 2013 and at the southeastern station (BB6) during summer 2014 (Figure 7).

In summer 2012, sperm whale clicks were detected at all stations except the nearshore one (BB4) (Figure 6). Sperm whale clicks were detected at all stations in summer 2013 (Figure 6). During overwinter 2013–2014 (Figure 7), sperm whale clicks were detected at both southeastern (BB6) and southern (BB10) stations on a few days during fall 2013 and spring/summer 2014. Sperm whales were detected before and after ice formation. The probability of occurrence of calls (Figure 8) decreased significantly with ice concentration for sperm whales (Wald's test: $\chi^2 = 10.6$, $p = 0.001$).

Figure 5: Maps of sightings in license areas by on-effort marine mammal observers from survey ships deployed during Shell's marine mammal visual monitoring and mitigation program from (A and B) 19 July to 16 October 2012 and (C and D), 1 August to 20 October 2013. Panels A and C show cetacean sightings, and panels B and D, pinniped sightings. In panels A and B, the green triangles represent 2012 summer stations, and in panels C and D, the orange triangles represent 2013 summer stations, and the black triangles, the 2013 – 14 overwinter stations.

Discussion

Narwhals, beluga whales, bearded seals, bowhead whales, long-finned pilot whales, and sperm whales were acoustically detected off West Greenland. While only a portion of the acoustic data was analysed due to the duty cycle of the majority of deployments, Tomisch *et al.* (2015) concluded that our method of analysing many short time frames is preferred, producing more accurate estimates than other methods (although continuous recordings would have been ideal). This technique has been found to be particularly effective on species that call regularly such as the species of interest here.

Narwhals were detected in spring and fall, showing a south-north migration pattern in spring and a north-south migration pattern in fall. During the open-water (sea ice free) period (July to September), narwhals were detected mainly at the more inshore stations. Similarly, Dietz and Heide-Jørgensen (1995) reported that during the open-water period, narwhals equipped with satellite transmitters were frequently found close to shore and glaciers within the Melville Bay Wildlife Sanctuary. In fall, narwhals move to the southern overwintering ground, a localised area of 23,125 km² in central Baffin Bay, where they reside from November through April (Dietz *et al.* 2001; Heide-Jørgensen *et al.* 2003a). Heide-Jørgensen *et al.* (1993) sighted narwhals along the western Greenland coast in March and April, primarily in the deep water at the southern entrance to Disko Bay. Our findings suggest that they pass through this area before returning to the summering grounds. The narwhals return to the summering grounds when the sea ice opens in June-July (Heide-Jørgensen *et al.* 2003c).

The detection period of beluga whale clicks during fall 2013 was very short and suggests a southward migration through Baffin Bay. Beluga whales from the Canadian High Arctic are known to migrate south along the northwestern Greenland coast through Baffin Bay in September-November (Doidge and Finley 1993; Heide-Jørgensen 1994). Previous studies have revealed that a large number of tagged beluga whales actually overwinter in the North Water Polynya (northwest Baffin Bay and Smith Sound) (Heide-Jørgensen *et al.* 2003c; Richard *et al.* 2001). Beluga whales have been found in a range of ice types (Moore *et al.* 2000; Suydam *et al.* 2001), but avoid dense pack ice (Barber *et al.* 2001) by overwintering in open water polynyas or loose ice (Heide-Jørgensen *et al.* 2003c; Richard *et al.* 2001). Our beluga whale detections from April to late May in 90% ice cover were therefore unexpected. It is generally assumed that most beluga whales overwintering in the North Water Polynya move southwest to the mouth of Lancaster Sound in April and early May (Koski *et al.* 2002) to summer in Canadian High Arctic archipelago (Richard *et al.* 2001). Even though beluga whales are seen occasionally in spring and summer on the Greenland side of the North Water Polynya (Heide-Jørgensen *et al.* 2013a), it is most probable that the beluga whales detected in the present study during spring 2014 were on route to the Canadian summering grounds in the High Arctic.

Bearded seals were mainly detected during spring, which coincides with their mating season (Cleator *et al.* 1989). The absence of call detections in our data while bearded seals were visually observed in the vicinity of our recorders in August to October 2013 confirms that this

species is vocally active during the mating period, but less loquacious at other times of year (Frouin-Mouy *et al.* 2016). We observed a trill (Figure 4) similar to the Canadian High Arctic trill labelled HCA3(T) by Risch *et al.* (2007). Interestingly, a patterned sequence was recorded in our overwinter database. This patterned sequence is composed of one long downsweep followed by three short downsweeps (cf. Figure 4). During a spring survey, Heide-Jørgensen *et al.* (2013a) detected bearded seals on ice floes and along the ice edge primarily over shallow water in the eastern part of the North Water Polynya. Also of interest, stations BB10 and BB6 were located in deep waters (1000 m and 575 m, respectively), suggesting that the bearded seal distribution in Baffin Bay is not limited to shallow areas as previously reported (Kovacs *et al.* 2011). Finley and Renaud (1980) reported that during a survey along the east coast of Ellesmere Island, Canadian Arctic Archipelago, more than 50% of bearded seals observed were in areas where the water depth exceeded 500 m. Other seal species were visually observed as well, but our detectors were not configured to detect their calls.

Few bowhead whales were detected during fall 2013 and spring and summer 2014. Their distribution is likely driven largely by migration patterns. Previous studies on movements of the Eastern Canada–West Greenland bowhead whale population show that these animals are widely distributed throughout the eastern Canadian Arctic and West Greenland where they perform long seasonal migrations (Heide-Jørgensen *et al.* 2003b). They overwinter in Hudson Strait, Cumberland Sound, West Greenland, and the North Water Polynya (Ferguson *et al.* 2010). In spring, they inhabit the west coast of Greenland (particularly Disko Bay, Tervo *et al.* 2009), Cumberland Sound, Foxe Basin, and Lancaster Sound in Canada (Ferguson *et al.* 2010). Their summer range includes the fjords and bays of the Canadian High Arctic, Hudson Bay, and Foxe Basin (Cosens *et al.* 1997). Bowhead whales use a wide range of habitats, suggesting flexible use of foraging areas (Nielsen *et al.* 2015), and this species may be expanding its distribution as suggested by its recent presence in the Northwest Passage (Heide-Jørgensen *et al.* 2011). Recent satellite-tracking studies (tagging in 2008–2010) showed that bowhead whales moved out of Disko Bay area between late May and early June (Laidre and Heide-Jørgensen 2012), and then followed the continental shelf north off West Greenland towards the northern part of Baffin Bay (Nielsen *et al.* 2015). Those observations are in agreement with bowhead detections in 2014 at stations BB10 and BB6 in early and late June, but do not explain the detections in April.

The presence of long-finned pilot whales along Baffin Bay has not been reported in the literature to date; however, in an aerial line transect survey conducted off West Greenland during August to September 2007, these whales were observed southwest of Greenland between 65°N and 68°N (Heide-Jørgensen *et al.* 2013b). In the present acoustic data, long-finned pilot whales were detected on several occasions at two offshore stations (BB5 and BB6; September 2013), and at the southern station (BB10) during fall 2013 (30 September, which matches visual observations of 100 individuals that day). Heide-Jørgensen *et al.* (2013b) mentioned that long-finned pilot whale sightings and catches were reported along the coast of Greenland from Qaqortoq to Upernavik between May and October, which suggests a summer-winter movement resulting from the spring bloom of primary production and subsequent prey abundance. Heide-Jørgensen

et al. (2013b) observed that long-finned pilot whales were present in deep offshore waters, with a preference for depths between 300 and 2000 m and at least 30 km from land. This suggests that pilot whales, whether traveling or foraging, are usually not found on the Greenlandic shelf, but primarily in the deeper waters beyond the shelf. Interestingly, long-finned pilot whales were most acoustically active in September 2013 at station BB5. This station is at the shelf edge, where upwelling may augment primary productivity. In long-finned pilot whales, vocal activity increases during foraging periods, with greater numbers of most whistle types produced when whales are spread over a larger area (Weilgart and Whitehead 1990). Our results demonstrate that long-finned pilot whales are present in the northern part of Baffin Bay at certain times of the year and are more acoustically active at the Greenlandic shelf edge, suggesting that their preferred prey may be there as well.

Results from the present study indicate that sperm whales were present in Baffin Bay, farther north than has been previously reported in the literature. On leaving their female relatives, which almost always inhabit waters deeper than 1000 m at latitudes less than 40°, the males gradually move to higher latitudes; the larger and older the male, the higher the average latitude (Whitehead 2002). Sperm whales have been reported to inhabit northern waters such as the Gulf of Alaska (Mellinger *et al.* 2004a) and the Norwegian Sea (Christensen *et al.* 1992; Madsen *et al.* 2002) during summer. In the present acoustic dataset, sperm whales were detected in August and September 2012 and from September to November 2013, before sea ice covered stations BB6 and BB10. They were also sporadically detected in summer 2014 from late June to late August after the sea ice disappeared.

The detection of sperm whales in our data may be explained, at least partially, by the distribution of its prey. Kawakami (1980) reviews studies of sperm whale diets and found that in most areas cephalopods (squid and octopods) form the bulk of their food source. The boreoatlantic armhook squid (*Gonatus fabricii*) is the most abundant squid in arctic and sub-arctic waters of the North Atlantic (Gardiner and Dick 2010). Due to its importance as food for sperm whales, Bjørge (2001) suggests that the distribution of the boreoatlantic armhook squid can, to a great extent, explain the presence of sperm whales in the Norwegian sea. Boreoatlantic armhook squid adults are common in oceanic mid-water, while juveniles occur in surface waters closer to the continents (Piatkowski and Wieland 1993). During summer, many juveniles occur in Davis Strait. Hatching begins off Kap Farvel at the end of April, and juveniles are transported up the West Greenland coast by prevailing currents (Kristensen 1984). They have been reported in our study area (Gardiner and Dick 2010). In Disko Bay, boreoatlantic armhook squid is believed to hatch in autumn and early winter (Kristensen 1984).

Given the relative paucity of marine mammal sighting data in Baffin Bay during the non-summer months, passive acoustic monitoring is a good tool to learn about the seasonal and inter-annual movements of marine mammals in this remote area. The present study, which documents the spatial and temporal distribution of several marine mammal species in Baffin Bay, helps identify the use of the oil and gas license areas by marine mammal populations. Year-round data collection provided baseline patterns of species occurrence to help gauge the

Figure 6: Percentage of recording days per month (normalized by effort) during which marine mammal calls were detected (from sperm whales, narwhals, and pilot whales) in August 2012, September 2012, and September 2013. The plus sign (+) indicates 0%.

management (mitigation) efforts needed in this area. Spring and fall detections of narwhals in the license area suggests that narwhals use the area for migrations. Few detections of beluga whales in spring suggest that they migrate through the project area without pausing to forage. Unsurprisingly, bearded seal vocalizations dominated the soundscape during the mid-May to mid-June breeding season. Bowhead whales were detected sporadically in spring, which agrees with our understanding of a highly variable spring migration of these whales. Long-finned pilot

whale calls were present along the southern continental shelf edge of the study area in August and September; this location is significantly north of previous reports of long-finned pilot whale distribution. Detections of sperm whales were unexpected and extend the range of sperm whales significantly north of previous reports, however, the presence of known sperm whale prey species suggests that these detections are reasonable.

Figure 7: Acoustical detections of marine mammals at stations BB6 and BB10, September 2013 to September 2014. Species detected are shown on left vertical axis. Black dots indicate detections; orange dashed lines, start and end times of recordings; and blue line, the temporal variation of sea ice concentration over the recording site. Ice scale is on the right axis.

Figure 8: Estimated relationship between the probability of call occurrence and the ice concentration for narwhals, bearded seals, and sperm whales (from observations at stations BB6 and BB10 over the winter of 2013 – 14).

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Chapter 8

Acoustic characterization of exploration drilling in the Chukchi and Beaufort seas

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Abstract

This paper characterizes underwater sound levels produced by three different drilling units during offshore exploration drilling at three sites in the Beaufort and Chukchi seas. Received levels and spectra are reported as functions of distance from each operation during drilling and excavation of mudline cellars (MLCs). Sound levels emitted during MLC excavation exceeded those during drilling at all three sites, although this operation was much shorter in duration. Drilling sounds exhibited tones below 2 kHz, with harmonics present to 10 kHz, while MLC excavation sounds were broadband in character. Drilling sounds varied substantially between the three operations, whereas, MLC excavation sounds were more consistent in amplitude and spectral distribution. Estimates of broadband and 1/3-octave band source levels were computed from measurements at 1 km range. The broadband drilling source levels were 168.6 dB re 1 $\mu\text{Pa}\cdot\text{m}$ for the *Kulluk* drilling unit, 174.9 dB re 1 $\mu\text{Pa}\cdot\text{m}$ for the drillship *Noble Discoverer*, and 170.1 dB re 1 $\mu\text{Pa}\cdot\text{m}$ for the semi-submersible *Polar Pioneer*. The received levels measured at 1 km during MLC excavation yielded source level estimates that were more consistent among the sources: 191.8 dB re 1 μPa , 193.0 dB re 1 μPa , and 193.3 dB re 1 μPa for the *Discoverer*, *Kulluk*, and *Polar Pioneer*, respectively.

Keywords: offshore, drill rig, sound signature, underwater noise.

Introduction

Alaska's outer continental shelf is believed to contain reserves of undiscovered oil and gas (MMS 2006). Oil companies have conducted exploration drilling at several locations offshore Alaska in the last fifty years to access these resources, using mobile offshore drilling units (MODU) that emit underwater sounds that could potentially disturb marine mammals and elicit behavioural responses such as a change of calling rates or modified distribution and migration patterns (Malme *et al.* 1989, Richardson *et al.* 1990, McDonald *et al.* 2012, Blackwell *et al.* 2015). The Alaskan offshore is inhabited by several marine mammal species important to the local subsistence communities, including bowhead (*Balaena mysticetus*), beluga (*Delphinapterus leucas*), walrus (*Odobenus rosmarus*), and several species of seals (Burns 1970, Moore and DeMaster 1998, Delarue *et al.* 2011, Jay *et al.* 2012, Hannay *et al.* 2013). Local hunters have concern that drilling sounds in the Alaskan Arctic could alter marine mammal distribution patterns and potentially reduce marine mammal availability as a subsistence resource if these animals move farther offshore than hunters can safely access. Assessment of the potential for this noise disturbance requires measurements of the underwater sounds from the MODUs operating in shallow Arctic environments.

In this paper we characterize the underwater sound levels emitted by two different drillships and a semi-submersible drilling unit that were measured during exploration drilling activities in the Chukchi and Beaufort seas, conducted by Shell (Shell Offshore, Inc., and Shell Gulf of Mexico, Inc.) in the summers of 2012 and 2015. Shell drilled top holes of two wells in 2012, one in the Chukchi Sea from the drillship *Noble Discoverer* (*Discoverer*) and one in the Beaufort Sea from the drillship *Kulluk*. They drilled a separate well in the Chukchi Sea in 2015 from the semi-submersible drilling unit *Transocean Polar Pioneer* (*Polar Pioneer*). Underwater sound levels were recorded during drilling at each of the three well sites using high-sensitivity, autonomous acoustic recorders moored at the seafloor.

Various support and supply vessels typically accompany MODUs. The proximity of these vessels often interferes with measurements of the noise emissions of the drilling units alone, because the vessels produce similar noise emissions. In 2012, a requirement from the U.S. Environmental Protection Agency limited the proximity to the MODUs at which supply and support vessels could remain for extended times. Access within a 25-mile (40 km) radius of each MODU was restricted, to minimize air emissions inside that zone. Vessels occasionally entered the 25-mile zone to conduct necessary operations but only for limited times. Consequently, this provided a unique opportunity to acquire high-quality acoustic recordings of drilling sounds without interference from ancillary sources. This regulatory restriction did not apply in 2015, so analysis of 2015 drilling sounds was limited to data acquired during shorter time periods when vessels were farther than 5 km from the acoustic recorders. Despite efforts to reduce the impacts of acoustic contamination from these other sources, low-level noise from ancillary vessels was present throughout most of the 2015 recordings.

This paper presents the measured sound pressure levels received at each recorder during

drilling and mudline cellar excavation. Spectral data and estimated source levels for each drill rig are provided. These source levels can be used with a propagation model to estimate underwater received levels over large areas around a drilling operation. This is useful for estimating marine mammal sound exposure levels, or to determine risk of acoustic impacts to marine mammals from future drilling operations at either the same or different locations.

Methods

Data acquisition

Underwater sound levels were recorded at 64 kHz sample rate and 24-bit resolution using autonomous acoustic recorders (AMAR-G3, JASCO Applied Sciences). Each AMAR was outfitted with a M8E-35dB omnidirectional hydrophone (Geospectrum Technologies Inc.; nominal sensitivity -164 dB re V/ μ Pa). The AMAR frames rested on the seafloor with the hydrophone mounted approximately 30 cm above the seabed.

The recorders were positioned logarithmically in distance along a radial away from each drillsites, at ranges of 1, 2, 4, and 8 km in 2012 and 0.5, 1, 2, 4, 8, and 16 km in 2015. The water depth was nearly constant at each drilling location (Figure 1). The nominal water depth at the Chukchi Sea sites was 46 m and 33 m at the Beaufort Sea site. In the Beaufort Sea, the recorders were set along a radial oriented southwest from the drill site, on the side of the rig closest to noise-emitting power generators. The recorders in the Chukchi Sea were oriented to intersect with the bowhead whale migration path, to the northeast in 2012 and to the north in 2015.

The AMARs were calibrated before deployment and after retrieval with a 42AC pistonphone calibrator (G.R.A.S. Sound & Vibration A/S), which generated a known 250 Hz reference tone accurate to 0.1 dB at the AMAR hydrophone sensors. The pressure calibration of each AMAR was obtained from the level of the reference signal in the digital calibration recording. Typical calibration variance using this method was less than 0.5 dB absolute pressure.

When the acoustic recorders were deployed, conductivity-temperature-depth profiles were sampled from the recorder-deployment vessel using either a Minos X or a Seabird SBE19 profiler. These data yielded the sound speed profiles used for this analysis.

Figure 1: Drillsites and recorder deployment locations in the Chukchi Sea (top) and Beaufort Sea (bottom).

Sound sources

Underwater sounds from MODUs primarily originate from on-board equipment vibrations, although some sound is transmitted directly into the water through vibration of the drill string and potentially also from interaction between the drill bits and the seafloor. The dominant noise sources are generally the vibrations and rotations of pumps, generators, engines, hydraulic winches, pipe-handling equipment, cranes, and other machinery on or below decks on the MODUs that transmit through the physical structure and radiate as noise into the water. Sounds from these sources exhibit characteristic tones at frequencies specific to the equipment rotation rates. Sounds are transmitted through the hulls of drillships and through the support legs and pontoons of semi-submersible drilling units. Machinery noise is predominantly concentrated at low to mid frequencies (10–1,000 Hz), and is dominated by strong tones at harmonics of mechanical rotation rates. Noise emissions into water are expected to be highest for structures that have large surface areas coupled to the water (Richardson et al 1995, Greene 1987, Gales 1982). Because drillships are mobile platforms that float on the sea surface, they require advanced dynamic positioning capabilities (typically used in deeper waters), or extensive moorings (typically in shallower waters), to accurately maintain their positions when high waves and currents are present. All the mechanical equipment and machinery are housed on or below decks and mechanical vibrations are usually quite well coupled to the ship's hull and, consequently, to the surrounding water.

The 2012 and 2015 drilling operations involved multiple phases. First, a narrow-diameter (around 25 cm) pilot hole was drilled approximately 400 m into the sediment at each site and a wider base conductor hole was drilled to a depth of approximately 105 m. Next, a 6-7 m diameter and 11-12 m deep cavity known as the mudline cellar (MLC) was excavated in the upper sediment (Figure 2) to house the wellhead and a blow-out preventer (BOP) under the maximum depth of potential ice gouge. MLC excavation was conducted using a 6-m diameter drill bit containing series of 0.9 m diameter rotating disks, powered by three hydraulic motors, and angled to displace seafloor sediment. Following this activity, a casing string was installed and cemented in place, after which the BOP was lowered and positioned into the MLC. This completed construction of the top-hole portion of the wells and this was the final stage of work at both wells in 2012. In 2015, deeper sediments were entered through further drilling, casing, and cementing operations, all conducted through the BOP.

Three different MODUs are characterized in this paper (Table 1) during drilling and during the excavation of the mudline cellars (MLC). Two of the MODUs, those analyzed in 2012, were both hull-based vessels equipped with drilling derricks. One, the *Discoverer*, was a self-propelled drill ship; the other, the *Kulluk*, was a circular drill ship without propulsion. The *Kulluk* had a double-sided, funnel-shaped hull with flared sides and was ice-strengthened with 76 mm thick reinforced steel. In addition to the drilling equipment, their noise-generating sources also included engines, generators, and hydraulic power systems. Sound was transmitted from machinery to the hulls by direct mechanical coupling to the vessel's internal structures, and weakly through airborne transmissions. In 2015 drilling occurred from the semi-submersible

drilling unit *Polar Pioneer*, which consisted of a main working platform supported by columnar legs mounted on submersed pontoons. The pontoons were at the water surface when it was floated to the drillsite and then submersed by ballasting with seawater once on site. The main platform and most of the support columns remained elevated above the sea surface and away from waves to provide operational stability (less movement). This also provided isolation between the water and the large surface area of the platform, reducing transmission of noise into the water column.

Figure 2: Common elements of an underwater oil well, including drilling rig, MLC, BOP, casing, and drill string. Generation of underwater noise takes place when mechanical energy from vibrating/moving structures couples into the water.

Table 1: Drilling platform specifications.

Drilling Unit	Operator	Length (m)	Width (m)	Draft (m)
Noble Discoverer	Noble Drilling	157	26	8.2
Kulluk	Shell	81	81	10
Transocean Polar Pioneer	Transocean Ltd	85	82	9.1 (transiting) 23 (drilling)

Data Analysis

Source levels for these large, spatially-distributed sources were determined indirectly by measuring the sound levels at distance and then applying correction factors to account for the amplitude reduction incurred by propagation from the source to the measurement location. Source sound levels for drilling and MLC excavation by each MODU were derived from measurements obtained at 1 km distance.

The recorded acoustic data were analyzed with custom processing software that computed spectral and broadband sound levels. The sound levels were calculated in 1-minute intervals by averaging 1 second Hanning-weighted time windows with 50% overlap. Power spectral density curves for periods identified in activity logs as “Drilling” or “MLC excavation” were averaged to obtain spectra for the respective activities. The activity logs did not contain sufficient detail to distinguish the phase of drilling, that is, whether the rig was drilling the pilot hole or a larger casing or conductor hole. This paper does not consider sounds recorded when casing or cementing occurred.

Source levels were derived by applying frequency-dependent transmission loss corrections in 1 Hz bands to the spectral levels measured at 1 km distance. Transmission losses for frequencies below 2 kHz were calculated using a wide-angled parabolic equation model (Collins 1993), adapted to account for shear wave loss through a complex density approximation (Austin and Chapman 2011). Frequencies of 2 kHz and greater were modeled using a ray tracing code (Porter and Liu 1994). Both models incorporated input parameters that included the geoacoustic properties of the seafloor (Table 2), the definition of bathymetry at the site, and the specification of sound speed in the water column as a function of depth. Results from Bayesian geoacoustic inversion of airgun modal dispersion data conducted in the area (Warner et al 2015) provided sediment geoacoustic parameters for the Chukchi Sea model. Geoacoustic model parameters for the Beaufort Sea were based on a geotechnical site investigation which provided descriptions of the cored sediment along with some physical properties for the first 30 m below the seabed (McClelland-EBA, Inc. 1986). This geoacoustic model was previously used to model underwater sound levels from drilling in the Beaufort Sea (Warner and Hannay 2011). Water depth was assumed to be a constant 46 m in the Chukchi Sea and 33 m in the Beaufort Sea. Sound speed profiles for the water column (Figure 3) were obtained from temperature and salinity profiles collected at the study sites during the sound measurement programs. Source spectral levels were integrated in 1/3-octave frequency bands to derive source levels for each MODU for frequency bands from 10 Hz to 32 kHz. Source depths were assumed to be one half of the draft of each rig; 4 m for the *Discoverer*, 5.5 m for the *Kulluk* and 18.5 m for the *Polar Pioneer*.

Table 2: Seafloor geoacoustic properties in the Chukchi Sea.

Depth (m)	Density (g/cm ³)	Compressional Wave Speed (m/s)	Compressional Wave Attenuation (dB/λ)	Shear Wave Speed (m/s)	Shear Wave Attenuation (dB/λ)
0–14.5	1.45	1630	0.26	98	0.13
> 14.5	2.32	2384	0.1		

Table 3: Seafloor geoacoustic properties in the Beaufort Sea.

Depth (m)	Density (g/cm ³)	Compressional Wave Speed (m/s)	Compressional Wave Attenuation (dB/λ)	Shear Wave Speed (m/s)	Shear Wave Attenuation (dB/λ)
0–2	1.6–2.0	1550	0.1–0.3	200	2.6
2–30	2.2–2.4	1674–1702	0.3–0.2		
30–200	2.4	1673–1843	0.2		
>200	2.4	1843	0.2

Figure 3: Sound speed profile for the Chukchi and Beaufort Seas.

Results

Figure 4 through Figure 6 are plots of the power spectral density curves and corresponding 1/3-octave band received levels for acoustic data recorded at 1 km distance from each MODU, during drilling and during MLC excavation. The mean values (solid lines) are plotted along with the 10th and 90th percentile values (dotted lines). The tight distributions in the plots indicate that the drilling and MLC excavation sounds were quite consistent throughout the recordings. Summation of the 1/3-octave band levels yielded broadband (10 Hz to 32 kHz) received levels at 1 km range from each source (Table 3).

The 1/3-octave band source sound levels (back-propagated from the levels received at 1km) for each MODU are plotted in Figure 7 through Figure 9. The derived 1/3-octave band source levels were summed through all frequencies to obtain broadband source levels for each source during drilling and MLC excavation (Table 3). During drilling, the *Discoverer* produced a broadband source level 4.8 dB higher than that of the *Polar Pioneer*, which in turn was 1.5 dB higher than the source level of the *Kulluk*. During MLC excavation, the broadband source level estimates for all three MODUs were within just 1.5 dB.

Acoustic data acquired during drilling activities indicated that the sound spectra for each MODU contained several tones. Dominant tones and harmonics occurred below 2 kHz, with higher harmonics present to 10 kHz. Tones below 100 Hz with harmonics at integer multiples of the fundamental frequencies corresponded with the expected operational frequencies associated with power generation equipment, engines, pumps, and motors on the rigs. The asynchronous vibrations of the shakers and agitators of the mud systems on the rigs elicited higher frequency tones. At frequencies below 500 Hz, peaks in the power spectral density curve were not as prominent relative to the background levels when the *Polar Pioneer* was drilling in 2015, compared to the peaks in the power spectral density curves of both the *Kulluk* and the *Discoverer* drilling in 2012. Noise from nearby vessels raised the background sound levels in 2015, since support vessels were not required to be at least 25 mi away from the well site (as they were in 2012) making tonal peaks in the spectral distribution appear less prominent at the lower frequencies.

Figure 10 through Figure 12 show plots of power spectral density levels measured simultaneously on recorders at several distances from the well sites during drilling and MLC excavation activities by each MODU. The received levels from the MODUs during MLC excavation were consistently higher than during drilling. The drill bit used for MLC excavation (6-m diameter) is significantly larger than that used for drilling (~50-cm diameter) so the onboard equipment is expected to be operating at higher power settings during MLC excavation, also with more pumping required. During MLC excavation the tones and harmonics were also dominated by sound with a more broadband nature. The power spectral density curves for MLC excavation by all three MODUs are more similar in structure and amplitude to each other than are those during drilling. There is also less variability between MODUs in their broadband source levels during MLC excavation.

The spectral density levels for most frequencies decayed with range, as is expected for sounds originating from the well sites. Measured data from 2, 4, and 8 km were compared with the curves of modelled transmission loss versus range from the sources. Example frequencies of 20 Hz (Figure 13) and 250 Hz (Figure 14) illustrate that the data measured at 2, 4, and 8 km range closely followed the modelled trends for sound decay for the respective locations. Similar trends were noted across all modelled frequencies. In some instances, the measured data exceeded the model estimates, which would be expected when background sound levels were elevated by support vessels, for example. During MLC excavation, the measured data at 20 Hz (Figure 15) deviated slightly more from the modelled loss curves, though the agreement was better at 250 Hz (Figure 16).

The specific contributors to the measured levels during MLC excavation could not be distinguished from the data. Some sounds could be expected to have originated from a combination of interactions of the MLC bit with the seafloor, from increased displacement and movement of seafloor materials during MLC excavation, or from sounds from the MLC bits or drive motors, transmitted directly to the water. Any sounds generated at or within the seafloor would be expected to decay with range more rapidly than sounds that propagate through the water due to attenuation in the seafloor. We configured the transmission loss model to calculate received levels resulting from a source placed at the seafloor rather than near the sea surface, but obtained a poor match to the measured data. Interaction of the drill bit with the seafloor is not likely a dominant sound mechanism.

Figure 4: Power spectral density (top) and 1/3-octave band received level (bottom) for measurements at 1 km distance from the Kulluk during Drilling (grey solid line) and MLC Excavation (black solid line) in the Beaufort Sea in 2012. Dashed lines indicate the 10th and 90th percentile received sound levels at each frequency.

Figure 5: Power spectral density (top) and 1/3-octave band received level (bottom) for measurements at 1 km distance from the Discoverer during Drilling (grey solid line) and MLC Excavation (black solid line) in the Chukchi Sea in 2012. Dashed lines indicate the 10th and 90th percentile received sound levels at each frequency.

Figure 6: Power spectral density (top) and 1/3-octave band received level (bottom) for measurements at 1 km distance from the Polar Pioneer during Drilling (grey solid line) and MLC Excavation (black solid line) in the Chukchi Sea in 2015. Dashed lines indicate the 10th and 90th percentile received sound levels at each frequency.

Table 4: Mean broadband (10 Hz – 32 kHz) sound levels (dB re 1 μ Pa) for drilling and MLC excavation. Source levels back-propagated to 1 m from data measured at 1 km range.

	<i>Kulluk</i> (Beaufort Sea, 2012)	<i>Discoverer</i> (Chukchi Sea, 2012)	<i>Polar Pioneer</i> (Chukchi Sea, 2015)
Drilling			
Source Level	168.6	174.9	170.1
Received Level at ~1 km	117.3	122.7	123.3
MLC Excavation			
Source Level	193.0	191.8	193.3
Received Level at ~1 km	138.9	140.4	141.8

Figure 7: 1/3-octave band source sound levels for the Kulluk derived from data collected at a 1 km range in the Beaufort Sea in 2012 during Drilling (thin blue line) and MLC Excavation (thick black line).

Figure 8: 1/3-octave band source sound levels for the Discoverer derived from data collected at a 1 km range in the Chukchi Sea in 2012 during Drilling (thick blue) and MLC Excavation (thick black line).

Figure 9: 1/3-octave band source sound levels for the Polar Pioneer derived from data collected at a 1 km range in the Chukchi Sea in 2015 during Drilling (thin blue line) and MLC Excavation (thick black line).

Figure 10: Power spectral density received levels for the Kulluk in the Beaufort Sea in 2012 as received at four ranges (1, 2, 4, and 8 km) during drilling (top) and MLC excavation (bottom).

Figure 11: Power spectral density received levels for the Discoverer in the Chukchi Sea in 2012 as received at four ranges (1, 2, 4, and 8 km) during drilling (top) and at three ranges (1, 4 and 8 km) during MLC excavation (bottom).

Figure 12: Power spectral density received levels for the Polar Pioneer in the Chukchi Sea in 2015 as received at six ranges (1, 2, 4, 8, and 16 km) during drilling (top) and MLC excavation (bottom).

Discussion

Underwater sound levels for the *Kulluk* were previously reported from measurements collected during drilling in the Canadian Beaufort Sea in 1984 (Greene 1987). Greene reported a broadband (20-1000 Hz) received level of 143 dB re 1 μ Pa at 0.9 km range, with the dominant 1/3-octave band level computed in the band centred at 400 Hz. The 1984 recordings did not exhibit significant tones above 90 Hz. However, several work boats were operating nearby (one of which was dragging for anchors) during the 1984 measurements and it was noted that the recordings contained significant sound from these work boats (Greene, 1987). The broadband received level measured at 1 km range from the *Kulluk* in 2012 was 117 dB, 26 dB less than Greene reported over a narrower frequency range. Broadband levels received at 1 km from the *Discoverer* (in the Chukchi Sea in 2012) and the *Polar Pioneer* (in the Chukchi Sea in 2015) were 5-6 dB higher than those from the *Kulluk* measured in the Beaufort Sea in 2012, but both were also 20 dB lower than Greene's reported levels for the *Kulluk*. Measurements at 1 km from the *Polar Pioneer* in 2015, during times when support vessels were within 2 km range of the recorder, exceeded by as much as approximately 20 dB those recorded when support vessels were more than 5 km distant, so it is reasonable that ancillary noise sources in 1984 could be the main cause of the large discrepancies between the Greene measurement and all the 2012 and 2015 data.

The smaller differences (5-6 dB) between the 2012 measurements of the *Kulluk* and those of both the *Discoverer* and the *Polar Pioneer* more likely reflect variability due to different rig designs and due to differences of operational conditions (equipment speed and power settings, drilling phase, etc). The specific operating conditions and settings of all on-board machinery during measurements were unknown. It is also notable that modernizations, including machinery vibration-isolation efforts and ice-reinforcement of the hull, were made to the *Kulluk* prior to the measurements in 2012. No dedicated measurements were made before and after the *Kulluk* modernizations to confirm whether, and by how much, the *Kulluk* modernization efforts might have reduced underwater sound emissions.

Source levels during drilling for each of the three MODUs considered in this paper are less than those for large commercial vessels (containerships, bulk carriers, vehicle carriers, cargo ships and tankers) operating at normal operating speeds, that can range between 177 and 188 dB re 1 μ Pa·m (McKenna *et al.* 2012). Drilling produces continuous noise over a similar range of frequencies as those that constitute typical vessel sound signatures. During MLC excavation, the MODU source levels exceeded those expected for sources such as vessels; this activity constituted the noisiest sounds emitted by the drilling operations. MLC excavation, however, occurred for a shorter portion of the drilling program; in 2015, the *Polar Pioneer* performed 238 total hours (~14 days) of drilling and 69 total hours (~3 days) of MLC excavation.

These measurements indicate that exploration drilling in the Arctic does not elicit sounds at levels sufficient to cause acute hearing injuries to marine mammals, though the generated sounds are at levels with potential at close ranges for behavioural disturbance to marine mammals or hearing impairment from long-term exposure. An analysis of the distances to which the

drilling and MLC excavation sounds could have the potential for marine mammal disturbance is beyond the scope of this paper, which is intended to be a source level reference, but is an area of related analysis that is being undertaken. Impact assessments that consider the spatial extent where there exists a potential for such disturbance can be well informed by the source level data derived in this work, but it is important to recognize the uncertainty of such assessments, given the variability of the measured levels and the assumptions inherent to the analysis. Also, the measurement arrangement did not allow an assessment of the directionality of the emitted sounds, and assumes that the sources can be considered omni-directional.

Figure 13: Measured spectral density levels at 20Hz for the Discoverer (Δ), Kulluk ($\circ$), and Polar Pioneer ($\star$) drilling, with solid, dashed, and dotted lines, respectively, showing modelled sound level decay with range.

Figure 14: Measured spectral density levels at 20 Hz for the Discoverer (Δ), Kulluk ($\circ$), and Polar Pioneer ($\star$) during MLC excavation, with solid, dashed and dotted lines, respectively, showing modelled sound level decay with range.

Figure 15: Measured spectral density levels at 250 Hz for the Discoverer (Δ), Kulluk ($\circ$), and Polar Pioneer ($\star$) drilling, with solid, dashed and dotted lines, respectively, showing modelled sound level decay with range.

Figure 16: Measured spectral density levels at 250 Hz for the Discoverer (Δ), Kulluk ($\circ$), and Polar Pioneer ($\star$) during MLC excavation, with solid, dashed and dotted lines, respectively, showing modelled sound level decay with range.

Summary

This paper reports measurements of underwater received levels and source levels from three different offshore MODUs that were engaged in drilling and MLC excavation for exploration drilling in 2012 in the Chukchi and Beaufort Seas and in 2015 in the Chukchi Sea. 1/3-octave band and broadband source level estimates were derived from these data. The highest broadband (10 Hz – 32 kHz) source level during drilling was ascribed to the drillship *Discoverer* operating in the Chukchi Sea in 2012 (174.9 dB re 1 μ Pa). The semi-submersible drilling unit *Polar Pioneer* in the Chukchi Sea in 2015 was the next highest (170.1 dB re 1 μ Pa). The *Kulluk*, operating in the Beaufort Sea in 2012, had the lowest broadband source level (168.6 dB re 1 μ Pa). Considering purely the physical structures of the different MODUs, it would be expected that the semi-submersible *Polar Pioneer* would have the lowest source level, since it has the smallest surface area for coupling mechanical vibrations from onboard equipment to the water. However, other factors such as the type of equipment and operational conditions (equipment speed and power settings, drilling phase, etc.) also influence sound emissions, in both amplitude and spectral structure. The sound levels for the *Polar Pioneer* are also slightly elevated by low level vessel noise from vessels which persisted throughout the recordings. The broadband source levels for MLC excavation were more consistent between the MODUs, differing by just 1.5 dB or less, with source levels of 191.8, 193.0, and 193.3 dB re 1 μ Pa for the *Discoverer*, *Kulluk*, and *Polar Pioneer*, respectively.

The spectral characteristics of drilling sounds had spectral maxima between 50 Hz and 300 Hz, and relatively linear decay with increasing frequency above 300 Hz. Spectra for MLC excavation were dominant at higher frequencies than drilling, with spectral maxima between 300 Hz and 1 kHz. This difference in spectral character places more MLC excavation sound energy in the hearing range of many marine mammal species, though both activities elicit sounds at frequencies that are within the hearing ranges of the bowhead, beluga, walrus and seals in the Chukchi and Beaufort Seas.

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Chapter 9

Synthesis and Conclusions

Synthesis

The purpose of this program was to advance the protection of marine mammals during the implementation of modern E&P activities through the following themes:

1. Define the state of knowledge and risks
2. Evaluate the efficacy of mitigation measures
3. Advance the scope and capacity of monitoring technologies
4. Implement advanced industry monitoring and mitigation measures to meet specific conditions and challenges
5. Provide measurement of heretofore unassessed E&P activities

The chapters in this thesis cover a wide range of topics, some of which may not appear to be directly related. Nevertheless, all the chapters in this thesis contribute to one or more of these themes, as indicated in the following sections, and thus to the overall purpose of advancing marine mammal protection during E&P activities.

State of the science¹

Over the past decade a significant number of studies have been conducted on the acoustic footprint of industrial activities and the associated effects of sound on marine mammals. Some of these studies focused specifically on the effects of hydrocarbon exploration and production, which have been summarized in Chapter 2. These collective efforts have improved our understanding of the sources used in E&P activities, how sound propagates in different environments, and the physiological and behavioral effects on the receptors. This increase in knowledge results in the improved ability to assess and mitigate effects. Nevertheless, there continues to be a large range of remaining data gaps, some of which are addressed in this dissertation. Many of these gaps have emerged as the knowledge base increased and are also driven by the three-dimensional expansion in scope around this topic.

Approximately 10-15 years ago, the main concern was mortality or injury (impact) to marine mammals (species) caused by airguns (source). The sheer volume of monitoring conducted around seismic operations has resulted in this concern decreasing. A shift was then observed to investigations into possible auditory effects of exposure. Over the past decade significant progress has been made in the field of Permanent Threshold Shift (PTS) and Temporary Threshold Shift (TTS) due to auditory and exposure studies in odontocetes, resulting in better, more fact-based, guidance and regulations. However, the issue of effects of sound on marine life has witnessed an expansion in focus from the perspectives of (i) the source - primarily air guns but increasingly also including drilling, pile driving, shipping and other geophysical equipment, (ii) the species groups - mainly marine mammals but increased focus on fish, invertebrates, and even plankton, and (iii) types of impacts - from mortality and injury to increased focus on disturbance and masking.

¹ Theme: Define the state of knowledge and risks

This three-dimensional expansion in scope has been accompanied with new and challenging knowledge gaps. Examples of these newer knowledge gaps are the effects of behavioral responses or masking in marine mammals and fishes caused by seismic surveys and the potential associated population-level consequences.

There is a three-dimensional expansion in scope associated with effects of sound on marine life that includes sources, species groups and impact types.

A risk-based approach towards monitoring and mitigation²

In this dissertation the results of several studies have been provided around monitoring and mitigation of E&P activities. Each of these studies contributed towards project-specific knowledge gaps and resulted in improved ability to manage risks of these E&P projects on marine mammal populations present in the project area. Although these different studies may not appear directly related, they are all real-world examples of activities conducted as part of the monitoring and mitigation framework depicted in Figure 1 in Chapter 1. Another feature these studies have in common is the sensitivity of the environment in which these activities were executed. This was largely driven by the presence of protected marine mammal species in relatively undisturbed areas, e.g. narwhal (*Monodon Monoceros*) in Baffin Bay, Greenland (chapter 3 and 7), North-Pacific gray whales (*Eschrichtius robustus*) off Sakhalin, Russia (chapter 4 and 5) and bowhead whales (*Balaena mysticetes*) in the Chukchi and Beaufort Seas (chapter 8).

The ‘As Low As Reasonably Practical’ principle (ALARP), which is introduced in chapter 2, advocates for a risk-based approach towards monitoring and mitigation of risk. In line with this principle, the studies included in this dissertation are good examples of higher-risk E&P activities that warrant more stringent mitigation and associated monitoring studies to enable adequate risk assessments and ensure adequate risk mitigation. For most of these projects, reliable and high-quality data were needed on abundance and density of marine mammal species. In addition, seasonal variation and project-specific acoustic propagation modeling studies were needed. These data were used for detailed impact assessments and design and implementation of associated risk mitigation measures. However, in the more ‘industrialized’ marine areas, or areas (or time periods) without the presence of endangered marine mammal species, where the risks are well understood, additional monitoring and mitigation activities may not be required. In these instances, adherence to regulatory requirements or international guidelines, such as those developed by Joint Nature Conservation committee (UK) or the International Association of Oil and Gas Producers, through the application of established knowledge-based best practices, may be sufficient.

The level of monitoring and mitigation conducted during E&P activities is usually, but not always, determined by regional or national regulations and/or global guidelines.

² Theme: Implement advanced industry monitoring and mitigation measures to meet specific conditions and challenges

The ALARP principle is not often applied in these regulations and guidelines, where often fixed sets of monitoring and mitigation measures are required or proposed, independent of the potential impacts. Future guidelines and frameworks would benefit from applying a more risk-based approach.

Monitoring and mitigation programs to manage risks of hydrocarbon activities on marine mammal populations should be risk-based.

CSEL³

Recently promulgated guidelines (e.g., Southall *et al.* 2019; NMFS, 2016, 2018) recommend use a period of 24 hours as the prescribed period for cSEL estimation in threshold criteria for the onset of auditory injury. As outlined in chapter 2, 24 hours is a rather arbitrary choice without clear biological significance. Some of the reasons why the 24 hour period lacks biological significance include (i) animals are not stationary and exposure to anthropogenic sound rarely continues for 24 hours due to animal movement as well as source movement for non-stationary sources such as seismic vessels, (ii) possible periods of silence within the 24 hours period are not considered, during which recovery of the hearing system occurs, and (iii) due to the logarithmic scale of sound propagation, it is mainly the closest distance between the source and animal that contributes to the total sound exposure level, which usually occurs in much shorter periods (<1 hour) than 24 hours. This is illustrated in Figure 1, which is based on the same dataset described in chapter 6 and 7. In this graph the accumulation of cSEL over a 12 hours period is depicted during which two seismic source vessels overpass a stationary recorder (Martin *et al.* 2019). The steepest increase in cSEL occurs during the first approach of the seismic source. However, the entire remainder of the passage of the first vessel plus the entire passage of the second vessel only increased the unweighted cSEL by 2 dB and the weighted SEL increased by even smaller amounts. Southall *et al.* 2019 and NMFS 2018 both acknowledge that the 24 hour accumulation period may not always be appropriate and that in some instances a shorter interval would be more appropriate in terms of considering multiple exposures as discrete events rather than continuing to accumulate noise energy, e.g. if activities last less than 24 hours.

Considering the arguments provided above, future guidelines may benefit from applying a shorter accumulation period that only captures the approach to the close point of approach (CPA) between source and receiver in a 24 hour period, as this captures most of the acoustic energy to which the receptor is exposed. This proposed methodology would also result in more simplistic and realistic exposure estimates.

Accumulation of exposure in non-stationary marine mammals over prolonged periods is mostly determined through animat models, where marine mammal distribution is assumed to be dynamic and dependent on the received sound levels. In these animat models, individuals' behavior, such as aversion, dive patterns, swim speeds, etc., is programmed to be dependent on

³ Theme: Implement advanced industry monitoring and mitigation measures to meet specific conditions and challenges

sound levels received by those individuals. As behavioral dose-response curves are not always well known, the outcome of these models is strongly dependent on assumptions included in the model. Especially over longer time-periods this can influence the accuracy of the exposure estimation. Use of the period including the approach to the CPA for estimation of cSEL may result in more accurate exposure estimates.

The 24 hours prescribed as the period for cSEL estimation in existing auditory injury threshold criteria lacks biological relevance and ignores recovery time during periods of silence. As an alternative, the use of the period covering the approach towards the CPA between source and receiver may result in more accurate exposure estimates and less complicated modeling efforts.

Figure 1: Accumulation of SEL over a 12-hour period on 4 Sep 2012 during the overpass of two seismic source vessels in Baffin Bay (M). The 10+ Hz SEL increased from 184.5 dB re 1 μ Pa²·s after the first vessel passed at 07:50 to 186.7 dB re 1 μ Pa²·s at 12:00 when the second passed. From Martin *et al.* 2019, for more information on this data set see Chapter 6.

Western North Pacific Gray whales⁴

The work presented in Chapter 5 on site fidelity in western North Pacific (WNP) gray whales is part of a larger WNP gray whale joint monitoring program executed by Sakhalin Energy Investment Company Inc. and Exxon Neftegas Ltd. This Joint Monitoring Program started in 2002 and consisted of studies on distribution, prey availability, acoustics, photo identification and behavior. It was established because of concerns of exploration and production activity in the near vicinity of the only known summer feeding area of WNP gray whales. This monitoring program, which is still ongoing, is unique because of its longevity and the consistent survey effort that was largely independent of industrial activities, i.e. in years without construction or seismic surveys, this program was implemented as well. In years with noisy activities, both Sakhalin Energy Investment Company Inc. and Exxon Neftegas Ltd. developed and implemented activity-specific monitoring and mitigation programs (e.g. Chapter 4), which were implemented independent of the Joint Monitoring Program.

Results of the Joint Monitoring Program have been instrumental in gaining more insights in the functioning, growth, demography and migration patterns of this vulnerable population. Furthermore, it provides an annual overview of the nature of anthropogenic activities in the area, effects of these activities on the population and can be used to estimate the potential consequences on population growth (Villegas-Amtmann 2015, 2017). Although the quantification of effects of hydrocarbon development in this area on the WNP gray whale population has not been part of this dissertation, population dynamics modeling studies demonstrate consistent growth of the population (Cooke 2017) despite these E&P activities.

Sakhalin Energy Investment Company engages with an independent panel ‘Western Gray Whale Advisory Panel’ established by the Independent Union for the Conservation of Nature (IUCN) (<https://www.iucn.org/western-gray-whale-advisory-panel>). Scientists on this panel review the results of the Joint Monitoring Program on an annual basis and advise the company on measures to reduce risk to the gray whale population. This collaboration has been ongoing since 2004 and has demonstrated the value of long-term and consistent engagement.

One key benefit of this long-term Joint Monitoring Program was that its learnings on gray whale migration periods and distribution and movement patterns could be directly applied for the development of specific mitigation measures. For example, results of the Joint Monitoring Program formed the foundation of the MMP described in Chapter 4, e.g. through insights on spring arrival times, behavioral study protocols, and data required to calculate the 95% abundance contour.

The primary reason for inclusion of photo-identification studies in the joint program was to monitor population dynamics and to determine a link between industrial development activities and population growth. However, these data can also provide insights in gray whale reproduction, mortality, health and injuries (including entanglement and ship strike), spatial movement and site fidelity. Because of the many applications of photo-identification data, it

⁴ Themes: Advance the scope and capacity of monitoring technologies, implement advanced industry monitoring and mitigation measures to meet specific conditions and challenges

is a very valuable monitoring technique. The study provided in Chapter 4 used these photo identification data to determine site fidelity of WNP gray whales to the Sakhalin summer feeding range and to determine movement patterns between the nearshore and offshore feeding ground.

This 13-year photo-identification study identified that most of the WNP gray whale population consistently returned to their summer foraging grounds in the Sea of Okhotsk on an annual basis, including 10 individuals that were sighted each year. There was no indication of immigration of non-calf individuals into the population and population growth was largely driven by reproduction. The WNP gray whales off Sakhalin displayed a high degree of site fidelity to both the nearshore and offshore feeding areas. More WNP gray whales made use of the nearshore feeding area, in comparison to the offshore area. This was especially the case during the early years of individuals, which may be due in part to more easily accessible food resources and a more protective environment from predators for young animals. There was consistent seasonal and multi-year movement between the nearshore and the offshore feeding areas. This included more seasonal movement of mature individuals from the nearshore into the offshore feeding area over the course of a season, and eventually reduced usage of the nearshore feeding area. The long-term nature of this photo-identification dataset, high rate of annual return of individuals to the feeding grounds, and the consistent trend of observing most “new” individuals as calves (as opposed to adults), along with little evidence of immigration allowed us to conclude that the gray whale population returning annually to Sakhalin waters is demographically self-contained. The nearshore and offshore Sakhalin feeding grounds are therefore important areas for summer feeding of young individuals and mothers, and mature animals, respectively.

The combination of (i) high site fidelity of WNP gray whales to the nearshore and offshore feeding ground, (2) absence of other known feeding areas in the Sea of Okhotsk, and (3) the relatively small spatial area of the nearshore and offshore feeding areas, makes this WNP population more susceptible to environmental changes and/or anthropogenic disturbance such as ice-coverage, fisheries or oil & gas development. Despite these factors this WNP gray whale population has seen an average growth rate of 4.3% between 2005 and 2015, but warrants continued focus to ensure this upward trend continues. Off Sakhalin, a greater understanding of WNP gray whales’ utilization, movement and site fidelity within their foraging habitat facilitated the development of new, or adjustment of existing, conservation management efforts of this population. Quantification of spatiotemporal movement parameters is also needed to better assess the potential population level consequences of disturbance in specific risk assessment frameworks. This is especially the case for use of bioenergetic models that require information on anthropogenic or natural factors affecting energy intake, energetic cost of movement patterns over the available feeding areas and difference in prey availability in these areas.

Long-term photoidentification efforts demonstrated that the western North-Pacific gray whale population off Sakhalin waters is demographically self-contained, with high site fidelity to both feeding areas, and demographic differences in area use.

Mitigation⁵

In line with the mitigation hierarchy, the most effective way of mitigating effects of sound on marine mammals is the avoidance in overlap of noise-generating activities with marine mammals in space and time. In some jurisdictions this is captured in some form by regulations and permit stipulations that block-out biologically important and sensitive periods such as migration, feeding or breeding. Unfortunately, avoidance in space and time is not always feasible, e.g. when marine mammal populations have a year-round presence, when weather conditions prevent operations in periods of marine mammal absence, or when activities take prolonged periods of time to complete. In those instances, the next step on the mitigation hierarchy – minimization – should be applied through identification of measures that reduce the exposure of marine mammals to industrial sound levels.

Mitigation of Permanent or Temporarily Threshold Shift (TTS) is a standard requirement for all hydrocarbon exploration and development activities. Because of extensive research on hearing thresholds and the onset of TTS in different marine mammal species over the past decade, the onset of TTS in most marine mammal species is understood quite well. The exception to this concerns baleen whales as taking hearing measurements in captured animals is not possible. Audiograms of baleen whales are therefore largely based on modeling efforts, such as finite element analysis of the middle ear. Because of these hearing and TTS-studies, effective mitigation measures, such as sound exposure-based shutdown criteria, can be implemented to reduce risk of TTS and PTS in seismic surveys and other industrial activities. In general, these zones of PTS and TTS are relatively small (< 2 km) and can usually be covered by Marine Mammal Observers.

More challenging is the mitigation of behavioral responses. In most seismic surveys it is difficult, if not impossible, to completely avoid behavioral responses and/or disturbance because of (i) the far larger impact zones, (ii) absence of behavioral onset acoustic thresholds and (iii) the range of severity in behavioral responses (i.e. from brief orientation changes to outright panic). Unlike PTS and TTS which typically have clear functional species group and frequency-specific onset criteria, there is much more variability in the onset of behavioral responses such as

(1) the activity state of animals exposed to the sound (e.g., feeding, nursing a calf, migrating, etc.), (2) the type and novelty of a sound, (3) the spatial relations between a sound and the animal hearing the sound (e.g., is the sound approaching or moving away), and (4) age–sex classes (Ellison *et al.*, 2011). Mitigation of behavioral responses, other than avoidance, is therefore not commonly observed in E&P projects. Most seismic surveys may not warrant the application of a behavioural mitigation threshold unless endangered or threatened marine mammal populations are in proximity to these activities. Over the past 5-10 years there has been a substantial uptake in studies on the link between behavioral responses/stress and population dynamics. A model, named ‘Population Consequences of Disturbance’, is developed for different

⁵ Themes: Evaluate the efficacy of mitigation measures, Advance the scope and capacity of monitoring technologies

species groups. Through detailed assessments of bio-energetic needs and costs, these models are contributing to our understanding of what level of disturbance a population can sustain before it affects population growth. Species- or Population-specific PCoD modeling assessments are useful to determine if behavioral responses should be considered, as they provide more insights in the likelihood of population-level impacts.

Despite the above-mentioned difficulty in mitigating for behavioral thresholds, in Chapter 4 we demonstrated that, in certain situations, mitigation for behavioral responses in endangered species or populations may be required and feasible. The seismic survey for which this mitigation and monitoring program (MMP) was designed and implemented, was exceptional in some ways because of its close proximity to a spatially limited, near-shore feeding area of WNP gray whales that could be monitored from shore with naturally elevated observation stations facilitating observations further from shore (>2km). These conditions were exceptional, and the methodology applied as part of this MMP is therefore not directly replicable in other seismic surveys, especially in offshore environments. However, specific elements of this MMP could be replicated in other situations. Development of this specific MMP far exceeded the standard measures applied to seismic surveys. The planning for development and implementation of the MMP was conducted as a collaborative efforts by the GWAP company-contracted scientists and took over 3 years and led to an effective plan that appeared to have met the objective of reducing risks to gray whales from the seismic survey. Implementation of this MMP was logistically and technically challenging, as it involved several vessels, multiple shore- and vessel-based monitoring teams, real-time sighting, behavior and acoustic monitoring, various channels of communication, and critical reliance on technical equipment in a remote environment. Costs associated with planning and implementation of this MMP were therefore also significantly higher compared to most MMPs. These additional efforts were considered necessary by the operating company Sakhalin Energy Investment Company Ltd. because of the small population of WNP gray whales and proximity to their feeding grounds. Chapter 4 provides an overview of this MMP, with more detail on analyses conducted using the data obtained during this monitoring program provided in five separate publications. These publications are captured in a special edition of the journal *Endangered Species Research* (<https://www.int-res.com/journals/esr/specials/seismic-survey-and-western-gray-whales/>).

The first two steps of the mitigation hierarchy, i.e. avoidance and minimization, are the most commonly applied ones, as described in chapter 2. The other two steps, restoration and offsetting, are rarely considered. This is for several reasons, an apparent lack of options being one of them. Offsetting impacts on marine mammal populations is nevertheless a field that warrants more consideration and creative thinking, as it could result in more effective conservation of marine mammal populations. Development and implementation of extensive monitoring and mitigation plans are often costly, and in some (but not all) projects the real conservation effectiveness may not be that obvious. In those cases, it may be worth funding other, more efficient, conservation activities. An example of this can be found in North Atlantic right whales (*Eubalaena glacialis*) who suffer from high mortality rates caused by ship strikes and entanglement in fishing gear. Instead of (or possibly in addition to) funding extensive MMPs

aimed at reducing disturbance of some individuals in this population, it may be more effective to co-fund activities that directly reduce mortality risks, such as, ropeless fishing gear programs or novel detection technologies. As monitoring and mitigation plans are often driven by regulatory requirements, this line of thinking could be considered by regulatory agencies,

Mitigation of behavior responses to seismic surveys may be warranted, when critically endangered marine mammal species are exposed, or if surveys may result in population level impacts.

Successful mitigation of behavioral responses is challenging and may be feasible only under specific conditions.

Use of Autonomous Unmanned Systems for marine mammal monitoring⁶

Aerial surveys of marine mammal populations are conducted to gain knowledge of the abundance, distribution, and behavior of marine mammals, as well as to assess the effects of human activities on these populations. Both the use of Unmanned Autonomous Systems (UAS) and manned aircraft for aerial surveys have their advantages and disadvantages, which are summarized in Chapter 3. Two important advantages of use of UAS as a platform for marine mammal aerial surveys are the reduced safety risks, especially in remote areas, and potential lower costs. Use of UAS for marine mammal aerial line transect surveys is not common at present. In order for UAS to become the preferred method of choice over manned aircraft, several requirements have to be met, including: a) detection of individuals in imagery should be comparable or better than detection probability by human observers, b) automated detection software needs to be improved to avoid high cost associated with human analysis and enable processing UAS-based imagery in near-real time and c) a manageable aviation permitting process to conduct UAV surveys beyond line of sight.

Chapter 3 in this thesis addressed the first of these requirements. This is the first published study where marine mammal population abundance estimates derived from both a digital image data set and an aerial human observation data set were compared. In this study we demonstrated that the detection probability and abundance estimation using commercially available camera-based systems in detecting marine mammal can be similar to human observers during aerial surveys. We compared image and observer-based population abundance estimates in the Melville Bay, Greenland. The applied methodology, and associated correcting factors, in image-derived estimates (strip census) was different than the methodology used for the aerial observers' sightings (Mark-Recapture Distance Sampling). The detection range in the images was also different compared to that of the observers (515 m vs. >2,000 m). Despite these differences the Melville Bay narwhal abundance estimates for these two methodologies were remarkably similar, and only differed by 2.4%. The image-based abundance estimate of 2,536 individuals

⁶ Theme: Advance the scope and capacity of monitoring technologies

(CV = 0.51, 95% CI: 1,003–6,406) was not significantly different than the aerial observer-based abundance estimate of 2,596 individuals, (CV = 0.51; 95% CI: 961–7,008). These results indicate that collection and analysis of high-resolution images can be an effective alternative approach to traditional manned aerial surveys for estimating cetacean abundance. It can provide similar estimates of abundance when appropriate correction factors are applied. Although during this survey a manned aircraft was used as a platform, UAV systems are available with enough payload to operate high-resolution camera systems. In other words, this particular narwhal aerial survey over Melville Bay could have been conducted using a UAV deployed from land or a vessel.

Koski *et al.* 2013 found that the camera system used in an imagery-based aerial survey lacked resolution to distinguish pinnipeds from debris at the outer edges of images. This indicates that for smaller marine mammal species, such as pinnipeds, the strip width may have to be truncated. The evolution of camera systems has resulted in a rapid improvement of resolution over the past decade. For that reason, it can be expected that this issue will resolve itself with the ever-rising increase in digital camera resolution.

A larger hurdle to use of imagery-based UAV surveys is the development of improved automated detection software. In our study it took 6 imagery analysts a total of 1,800 hours to analyze the 20,936 images taken during the Melville Bay survey. For most aerial surveys this would be unacceptable due to prohibitive imagery analysis costs, and the need for instant results during monitoring studies. Further improvements in analytical software, especially through Machine Learning/Deep Learning, are therefore required to process many high-resolution images faster, more accurately and in near-real time. For UAV-based marine mammal surveys to be truly competitive with human-based aerial surveys, the UAV will need to be equipped with an integrated camera, GPS, imagery-processing computer system and communication channels to a ground-station, enabling communication of near real-time observations. Presumed positive marine mammal identifications in an image made by automated detection software can be automatically clipped from the image for purpose of file size reduction and transmitted to a ground station for verification by a human analyst. A system like this would result in near-real time survey results that are safer, auditable and potentially cheaper as well. Another significant hurdle involves the required aviation permits needed to allow the safe use of UAV for surveys over the horizon (Beyond Visual Line of Sight (BVLOS)). Whereas permitting is a significant hurdle for BVLOS UAV surveys, once these technologies become more common it may result in more streamlined regulations for UAV surveys.

Despite these hurdles the future for UAV-based aerial marine mammal surveys looks promising. There is a significant amount of marine mammal aerial survey work being executed on a global scale, making investments in furthering this technology attractive.

Abundance estimates based on imagery-based aerial datasets can be comparable to human-observer based estimates, for certain marine mammal species.

For autonomous aerial marine mammal survey to become the standard, there is a need for better, commercially available, automated software detection.

Passive Acoustic Monitoring⁷

Passive Acoustic Monitoring (PAM) is a valuable tool for both marine mammal and acoustics studies as described in Chapters 2, 4, 6, 7 and 8. One benefit from deploying PAM systems is that, in principle, it can provide valuable data on marine mammal presence and natural or anthropogenic sound levels at the same time. This is demonstrated by Chapters 6 and 7, on marine mammals and seismic surveys sound levels, respectively, which are both based on data obtained by the same recorders. Another important benefit from PAM systems is the ability to provide year-round information of areas that are not always accessible for human observations, such as Arctic areas covered in winter-ice. These year-round observations on marine mammal presence and the acoustic soundscape provide new insights in the seasonal and spatial variation in abundance and distribution of populations, and their potential for exposure to natural and anthropogenic sound sources.

Baffin Bay – Marine Mammals

The Passive Acoustic Monitoring study in Baffin Bay, Greenland, involving year-round deployed recorders in and near a hydrocarbon license area used for exploration surveying, contributed to our understanding of the spatial and temporal distribution of several marine mammal species in Baffin and Melville Bay. It also provided insights into the use of the oil and gas license areas by these populations. Baffin Bay is a good example of an inaccessible Arctic winter area resulting in relative paucity of marine mammal sighting data in Baffin Bay during this period. Observations on species occurrence obtained during this year-round data collection effort would have helped gauge the management (mitigation) efforts needed in this area should further hydrocarbon development in this area have taken place. Some key observations of this study were spring and fall detections of narwhals in the license area suggesting that narwhals used the hydrocarbon license area for migration. Few detections of beluga whales in spring suggested that they migrate through the project area without pausing to forage. As expected, bearded seal vocalizations made a significant contribution to the soundscape during the mid-May to mid-June breeding season. Bowhead whales were only detected sporadically in spring, which was in line with our knowledge of the highly variable spring migration of this species. Two extralimital observations were made during this study. Long-finned pilot whale calls were present along the southern continental shelf edge of the study area in August and September; this location is significantly north of previous reports of long-finned pilot whale distribution. Furthermore, detections of sperm whales were unexpected and extend the range of sperm whales significantly north of previous reports. This is not entirely unexpected based on known presence of sperm whale prey species. PAM proved to

⁷ Advance the scope and capacity of monitoring technologies, implement advanced industry monitoring and mitigation measures to meet specific conditions and challenges

be a useful tool to learn about the seasonal and interannual movements of marine mammals in this remote area.

Use of Passive Acoustic Monitoring provides important information on seasonal and interannual presence and movement of marine mammals in Baffin and Melville Bay, including two extralimital observations of long-finned pilot whales and sperm whales.

This study further confirmed the value of this tool in remote and inaccessible (arctic) areas.

Baffin Bay – Acoustic monitoring and verification⁸

The acoustic (PAM) study of the natural soundscape and anthropogenic sound levels produced by the 2012 seismic survey, conducted by two simultaneous operating vessels, provided numerous learnings as well in Baffin and Melville bays. Due to its remoteness, the natural soundscapes of Melville and Baffin Bay typically showed minimal man-made sounds. The soundscape of Melville bay was dominated by glacial ice sounds as measured by the nearshore recorder (BB4) deployed in Melville Bay. The median 1-min SPL recorded by BB4 was 116 dB re 1 μ Pa, i.e. 14 dB higher than the 102 dB re 1 μ Pa at the ice-free Station BB7 (north-west corner of license area) in summer 2013. The seismic survey that was conducted in 2012 substantially raised the acoustic profile on all recorders, except for the nearshore Melville Bay recorder (BB4) where only rarely seismic pulses were detected. The average 1-min SPL at the most centrally deployed station (BB1) was 106 dB re 1 μ Pa prior to the start of the survey (2 August 2012) and 134 dB re 1 μ Pa after that date, i.e. an average increase of nearly 30 dB re 1 μ Pa. Most of this increase occurred at frequencies below 100 Hz. Logically, the received sound levels at that station increased and decreased as the survey vessel approached and departed.

Another unexpected observation was the presence of strong multipath arrivals at distances of less than 40 km. At 40 km the pulse length ranged from 2 to 6 seconds and contained up to 20 distinct multipath arrivals and depended on propagation variables such as e.g. bathymetry, bottom scattering roughness, weather, etc. Whereas it is normal for the seismic pulse length to become longer with distance, and sometimes develop multi-path arrivals, these extreme pulse-lengths and number of multi-path arrivals are uncommon. This also applies for the similar amplitudes observed for the direct arrival and subsequent multipath arrivals, which was not previously observed.

Acoustic measurements taken during this study were used to assess the distance to existing injury thresholds after applying M-weighting for different functional hearing groups. The Southall *et al.* (2007) weighting functions and thresholds that were applied on measurements predicted potential hearing damage for pinnipeds at ranges of 600 m. from the vessel and hearing

⁸ Advance the scope and capacity of monitoring technologies, implement advanced industry monitoring and mitigation measures to meet specific conditions and challenges

injury to low-frequency cetaceans at very close ranges (<100 m.). The NOAA Technical Guidance (NMFS, 2016) weighting functions and thresholds applied on measurements predicted that the acoustic energy from this survey could injure high-frequency cetaceans at ranges of less than 500 m. This survey applied shut-down criteria of 800 m. for cetaceans and walrus and 500 m. for other marine mammal species. This suggests that the applied mitigation measures were sufficiently precautionary to prevent PTS.

Although acoustic modeling studies are conducted regularly to determine impact zones or longer-range sound levels, few technically adequate modeling verification studies are conducted to determine the accuracy of prediction and identify opportunities for improvement. In our study, a long-range propagation modeling study was conducted prior to the execution of the seismic survey and measurements were compared with these results. It was found that the pre-survey modeled results were 3-7dB higher than the measured values at ranges over 500 m. Reparameterization of the model with bathymetry and sound speed profile measured during the survey improved the outcome to 0-4 dB up to 65 km. This demonstrates that long-range sound propagation modeling studies can be accurate but rely on the availability of high-fidelity environmental model input data.

Furthermore, these recordings confirm previous reports that seismic airgun sounds include energy up to at least 30 kHz although most of the energy in seismic pulses is in the 50-1000 Hz range. The SPL in the band used by dolphin species for social whistle communications (16 kHz octave band) were increased by 20 dB compared to the ambient levels measured in September 2013 at ranges of 6 km from the source vessels, providing some indication of possible masking zones.

The acoustic footprint of these two seismic vessels increased the soundscape in Baffin Bay with an average increase of nearly 30 dB re 1 μ Pa for the period of the seismic survey.

Long-range acoustic propagation studies can be accurate and depend on high-fidelity environmental model input data.

Chukchi and Beaufort Seas – Acoustic source monitoring⁹

Acoustic monitoring for purpose of verification of source and propagation modeling is more common for seismic surveys than for drilling activities. This is mainly driven by louder sound levels associated with seismic surveys and increased risk of impact to marine mammals. However, drilling activities in very sensitive areas, such as the Chukchi and Beaufort seas, warrant more monitoring requirements as well, as these seas provide important habitat for several marine mammal species such as bowhead (*Balaena mysticetus*), beluga (*Delphinapterus leucas*), walrus (*Odobenus rosmarus*), and several species of seals. Concerns over effects of drilling sounds on these populations by local

⁹ Themes: Implement advanced industry monitoring and mitigation measures to meet specific conditions and challenges. Provide measurement of heretofore unassessed E&P activities

communities, regulatory agencies and conservation organizations, combined with the lack of available data, resulted in the need for an assessment of actual sound levels of drilling and mudline cellar excavation by three different Mobile Operating Drilling Units (MODUs). Underwater sound from MODUs originate primarily from on-board equipment vibrations but also from the interaction between drill bit and the sea floor. Based on measurements taken at 1 km range, the drill ship Discoverer operating in the Chukchi Sea in 2012 was found to have the highest broadband (10 Hz–32 kHz) source level during drilling (174.9 dB re 1 μ Pa). The semi-submersible drilling unit Polar Pioneer in the Chukchi Sea in 2015 was the next highest (170.1 dB re 1 μ Pa). The Kulluk, operating in the Beaufort Sea in 2012, had the lowest broadband source level (168.6 dB re 1 μ Pa). These source levels are typically lower than those for large commercial vessels (containerships, bulk carriers, vehicle carriers, cargo ships, and tankers) operating at normal operating speeds, that can range between 177 and 188 dB re 1 μ Pa m (McKenna *et al.*, 2012). The spectral characteristics of drilling sounds had spectral maxima between 50 and 300 Hz, with decreasing spectral density levels above 300 Hz. Drilling of the mudline cellar (MLC) was found to be the loudest activity, with 191.8, 193.0, and 193.3 dB re 1 μ Pa for the Discoverer, Kulluk, and Polar Pioneer, respectively. This activity occurred for a shorter portion of the drilling programs. The Polar Pioneer performed 238 total hours (~14 days) of drilling and 69 total hours (~3 days) of MLC excavation in 2015. These MLC excavation sound levels were more broadband in nature with higher frequencies compared to drilling. The knowledge obtained during this acoustic monitoring study would have resulted in less uncertainty in future drilling impact assessments for this area. However, as this exploration program was unsuccessful in finding economic quantities of hydrocarbon deposits, and development in this Arctic offshore environment was challenging, no further drilling activities were executed in this area.

Offshore drilling activities generate loud sound levels but are generally lower compared to other large commercial vessels, except for mudline cellar excavation.

Future research needs

Some of the studies described in this dissertation pushed the boundaries in terms of novel approaches towards monitoring and mitigation, e.g. using digital aerial monitoring systems to determine population size (chapter 3), or mitigation for behavioral responses in western gray whales (chapter 5). With regards to the gray whale behavioral mitigation study, other, more recent, programs in this area have used the design and learnings from this study and have implemented similar programs.

In most of the chapters in this dissertation, new insights are provided that are essential for robust application of the Source (chapter 5, 6, 8), Pathway (chapter 5, 6), Receiver (chapter 3, 4, 5, 7) model. In future impact assessment efforts for E&P projects in similar environments, using similar sources, or affecting similar species, results of these studies will directly contribute to an improved ability to assess and manage risks of those projects to marine mammals. The six field studies presented in this dissertation have therefore contributed towards closing or reducing

specific knowledge gaps as described in the respective chapters.

Despite the large body of research on the effects and impacts of sound associated with E&P activities on marine mammals, key knowledge gaps remain. In addition to project-specific knowledge gaps, such as seasonal and spatial distribution of populations in a specific area, some key future research needs can be summarized as following:

Source: There is a need for detailed source characterization of non-seismic sources, such as pile driving and other geophysical equipment (e.g. side scan sonar, sub-bottom profiler, boomers, sparkers, etc.). Another key priority is the development of alternative sound sources that could reduce impacts on marine life, such as commercially available marine vibrators.

Pathway: More long-range propagation modeling verification measurements in different environmental conditions are needed to determine the accuracy, and need to improve, acoustic modeling over long ranges (10-100 km.) and in different environments.

Receiver: Audiograms and TTS measurements for a wider range of species are needed to depend less on interpolation between species, including development of novel methodologies to derive these in low-frequency species such as mysticetes. The role of hearing recovery between pulses, or period of silence within activities, is needed when applying metrics for injury thresholds, as recovery in periods of silence is currently not considered. Also, more studies on the application of hearing weighting functions in the assessment and mitigation of behavioral responses, disturbance and masking are required. Another key research priority is the continued improvement and application of Population Consequences of Disturbance (PCoD) models to understand the “so-what?” aspect of behavioral responses, i.e. which type of responses, under what conditions (seasonality, duration, context, etc.), have a biological significance at a population level. These models could also be applied to better understand the issue of cumulative or aggregate impacts of multiple activities occurring in the same area, either at the same time or within the same season.

Monitoring: The E&P industry and marine mammal conservation society would benefit from further development of autonomous monitoring technologies, such as autonomous operated camera-based aerial systems described earlier in this chapter, or PAM arrays, to monitor (changes in) abundance and distribution of marine mammal populations in normal and poor visibility conditions.

Mitigation: For those E&P activities that generate sound without a purpose, such as drilling, piling and shipping, effective quieting technologies will be instrumental to reduce sound levels. Furthermore, an assessment of the efficacy of common mitigation measures should be most useful to ensure measures are indeed protective. Lastly, the concept of offsetting impacts on populations warrants more creative thinking as in some cases, marine mammal populations may benefit more from conservation activities that are not directly related to E&P activities.

The role of industry, technology and collaboration

Whereas the key findings and results have been provided in the previous sections of this dissertation, it is worth reflecting on some other important aspects of this work. Specifically, on the role of industry-sponsored monitoring, technology development and collaboration with external stakeholders.

The different studies outlined in this dissertation provide in-depth insights into some of the monitoring and mitigation efforts and studies that are initiated by the E&P industry. Drivers behind these studies can be regulatory requirements, internal company standards, external stakeholder concern, or the need to reduce risk of specific E&P activities. A large part of the knowledge on effects of underwater sound on marine mammals originates from the academic community, for example through studies using captive animals or through field studies. The E&P industry has augmented this knowledge base by funding external research and conducting monitoring and mitigation studies during E&P activities, such as the ones outlined in this dissertation. Because of the scale of E&P activities and associated logistical and financial challenges, it is not often feasible to conduct these studies in controlled environments. For example, conducting a meaningful behavioral response study using a full-scale seismic source requires extensive funding and planning. This is where well-designed monitoring studies conducted as part of actual E&P operations are of value (e.g. chapter 5), as they provide necessary insights into actual sound levels and associated effects on marine mammals. In summary, the E&P industry has an important role to play in expanding the knowledge base on the effects of E&P activities on marine mammals. Collaboration with the academic, conservation and regulatory community should be an integral part of those efforts.

Technology development has a key role in our efforts to manage risks to marine mammals. Monitoring technology, such as Passive Acoustic Monitoring (PAM) systems, has seen a rapid improvement over the past decade and continues to develop at great pace. This includes telemetered PAM systems, as used in the Sakhalin western gray whale study (chapter 5), enabling real-time measurements and transmission to shore-based receiving stations. Further development and improvement of the different sensors and platforms used in marine mammal monitoring technologies will aid more effective, cheaper and safer ability to monitor the presence of animals and responses to anthropogenic influences. The use of camera systems on UAS, as described in Chapter 3, is another example of this. Although these UAV systems are currently not operationalized for marine mammal line transect surveys, the study in chapter 3 has demonstrated that they have great potential for replacing high-risk aerial surveys using human observers. Over time and with sufficient funding for additional R&D, detection and observations of marine mammals are likely to become largely autonomous, real-time and at reduced cost.

The collaborative nature of the monitoring and mitigation studies outlined in this dissertation, is another important aspect worth emphasizing. Not only is it well recognized that stakeholder engagement is a fundamental part of project execution, especially when there is opposition to certain projects, but development and execution of these studies requires (outside)

expertise in a broad set of disciplines. To illustrate this point, the design and execution of the six field studies in this thesis involved the input and contribution of numerous universities, research institutes, (inter)national conservation organizations, technology providers, independent experts and scientists, regulatory agencies, Non-Government Organizations and other International Oil Companies. All these stakeholders have their own views on the technical aspects of monitoring and mitigation programs and the level of marine mammal conservation needs. Whereas these views are not always aligned, extensive collaboration almost always results in better alignment of those views. Cross-disciplinary learning is another benefit of these engagements as collaborating parties learn about different aspects of these E&P projects and conservation needs. For example, conservation or marine mammal scientists involved in these programs gained a better understanding of the technical aspects and drivers behind E&P activity execution, resulting in an improved ability to advise on design of mitigation measures. E&P engineers, on the other side, through working with the marine mammal scientists, were observed to gain a better appreciation for specific marine mammal species and the need to manage risks to these species adequately.

Conclusions

The previous sections provided an overview of how they addressed the different themes, and how they contributed to the overall purpose of advancing the protection of marine mammals during the implementation of modern E&P activities. A detailed overview is described of the most recent knowledge on the effects of E&P sound on marine mammals, as well as a description of the key risk factors (chapter 2). This knowledge base has improved significantly over the past decade, but key knowledge gaps remain as they relate to species, sources, and impacts. Examples of novel mitigation measures and their efficacy are provided in chapter 5. This concerns a successful effort to mitigate the auditory and behavioral effects of a 4D seismic survey on western North Pacific gray whales and includes a detailed assessment of the efficacy of these measures. Application of the ALARP-principle called for more stringent measures during this survey, due to several factors such as proximity of E&P activity to critically important feeding grounds and the protected status of this population. A practical example of the role of advanced technology in monitoring presence and behavior of marine mammals is provided in this study as well. The integration of a Geographical Information System with theodolite observations and real-time verification of propagation models (through telemetered Passive Acoustic Monitoring systems) resulted in the ability to obtain real-time gray whale exposure levels on their nearshore summer feeding ground. Advancing technology is also a fundamental theme in chapter 3, in which it was determined that use of Unmanned Aerial Systems (UAS) for estimating marine mammal population estimates has great potential, despite some key regulatory and data processing hurdles. The implementation of advanced industry monitoring and mitigation programs (MMP) is a central theme in all studies described in this thesis. The drivers behind these MMPs range from regulatory requirements (chapter 6 - 8), stakeholder concerns (chapter 4- 5), company-specific requirements (chapter 3) or to fill knowledge gaps around unassessed E&P activities (chapter

8). The acoustic characterization of exploration drilling in the Chukchi and Beaufort seas is an example of unassessed E&P activities, as few measurements of arctic drilling activities were made previously but were crucial for improved future risk management.

Through addressing these different themes, the studies in this dissertation have contributed to the advancement of protection of marine mammals during implementation of E&P activities. Although more effort is required, this is one step closer towards the goal of ensuring co-existence between E&P, and other energy-generating, activities and marine mammal populations.

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Appendices

Epilogue

Co-authors

Summary

Samenvatting

Acknowledgements

About the author

Publications

Epilogue

Most of my professional focus over the past 13 years has been on managing the effects of offshore E&P activities on marine mammal populations. This dissertation is a summary of some of the key projects I worked on. Whereas it can be challenging to prove the presence or absence of a population-level effect caused by specific anthropogenic activities, it is my personal impression that the IOC (international oil companies) E&P industry is, in general, sufficiently protective of marine mammal populations.

However, the times are changing.

In response to climate change concerns, Shell has made significant carbon-related short- and long-term commitments. The company strives to be a Net-zero emissions energy business by 2050 in step with society, which will require significant changes to its direction and strategy. Oil and gas exploration and production will continue to occur although, proportionally, the contribution of renewable sources of energy to the total energy mix will increase significantly.

One pillar to achieving these carbon ambitions is the growth of Shell's renewable power generation business. Offshore wind development will play an important role in Shell's portfolio. Large-scale offshore wind development comes with its own set of ecological issues and challenges. For example, pile driving of monopiles with a diameter of 10-15 meter generate loud in-water sound levels that can impact marine mammals, and other aquatic life, similar to seismic surveys.

Many of the marine sound monitoring and mitigation requirements, knowledge gaps and research programs conducted in the E&P industry, are directly applicable to pile driving activities as well, e.g. hearing and TTS thresholds for marine mammal species. The offshore wind sector further builds on this available knowledge by identifying information gaps and initiating new industry-specific initiatives to avoid and reduce effects of pile driving.

In line with these energy transition developments, my scope has changed and I'm now working in Shell Renewables and Energy Solutions with key focus on managing environmental effects of offshore wind development, including effects of pile driving. I'm hopeful that these efforts will contribute to a more sustainable environment where marine mammal populations can co-exist alongside renewable energy development.

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Summary

Offshore Exploration and Production (E&P) activities, such as seismic surveys and drilling generate sound that propagates well in marine environments. These activities can overlap in space and time with marine mammal populations in different stages of their life cycle. Depending on the sound levels, frequency and duration, marine mammals can be impacted by these sound sources. Exposure of marine mammals at varying distances from a sound source can result in different effects ranging from auditory injury, i.e. Permanent Threshold Shift (PTS), Temporary Threshold Shift (TTS), to behavioral responses or disturbance and communication masking. If these sound effects are severe, or continue for prolonged periods of time, and are not mitigated sufficiently, they may result in population level consequences. Marine sound risk assessments requires information on (i) the acoustic characteristics of the *source* such as source level, frequency spectrum and duty cycle, etc., (ii) the *pathway*, i.e. the way that sound propagates through the water column, and is affected by environmental and physical conditions and (iii) *receptor* specifics such as abundance and distribution and associated seasonal variation, species-specific audiograms and TTS thresholds, sensitivity of species to disturbance, etc. A range of measures can be applied to mitigate these effects.

In Chapter 2, a comprehensive overview is provided of these types of effects and available mitigation measures that can be applied to mitigate these effects. In this summary, the source-pathway-receiver (SPR) model is applied to summarize the current understanding of 1) E&P impulsive sound sources such as air gun arrays and continuous sounds originating from drilling (source), 2) the propagation of sound generated by these sources through the ocean's water column (pathway) and, 3) the effects of these sounds on marine mammals (receiver). Potential unmitigated effects of E&P activities on marine mammals can be categorized according to their impact severity and spatial scale, ranging from severe effects occurring at a small spatial scale to lower level effects occurring at larger scales (typically, but not always, in the following order: permanent auditory threshold shift → temporary auditory threshold shift → behavioral disturbance → masking). Available monitoring techniques, applied to enhance our understanding of marine mammals as related to E&P effects ranging from individual behavioral responses up to population level consequences, are also described in this chapter using the SPR model. Additionally, an overview of mitigation measures applied in the E&P industry to prevent unacceptable impacts to marine mammals are provided and categorized according to a mitigation hierarchy (avoid > minimize > restore > offset). Finally, a case is made for application of the ALARP (As Low As Reasonably Practical) principle in seismic mitigation guidelines; that is, the applied mitigation measures in specific E&P activities should be proportional with the assessed risk on marine mammal populations, as well as reasonably practicable to achieve.

In chapter 3 a study is presented on a comparison of abundance estimates of a narwhal population in Melville Bay, Greenland, based on an aerial double-observer line-transect (MRDS) survey

and an image-based strip survey. The goal of the study was to determine if camera systems on Unmanned Aerial Systems (UAS) could provide similar abundance estimates as human observers on planes. This is the first published study where marine mammal population abundance estimates derived from a digital image data set and an aerial observation data set were compared. From 25–30 August 2014 a double-observer line-transect survey was conducted over Melville Bay, home to one of two summering populations of narwhal (*Monodon monoceros*) off West Greenland. A total of 1,932 linear kilometers was surveyed along 33 transects. In addition to using observers (4), the aircraft was equipped with two oblique cameras to capture a comparable data set. Analysts reviewed the images for narwhal sightings, which were then matched to the observer sightings. Other objectives of the study were to determine advantages and disadvantages of the detection capabilities of both methodologies, and to conduct a comparative analysis of population abundance estimates. Correcting for the truncated detection distance of the images (500 m), the image analysts recorded more sightings (62) and a lower mean group size (2.2) compared to aerial observers (36 and 3.5, respectively), resulting in comparable numbers of individuals detected by both platforms (135 vs. 126). The abundance estimate based on the image sightings was 2,536 (CV=0.51, 95% CI: 1,003–6,406), which was not significantly different from the aerial observers estimate of 2,596 individuals (CV = 0.51; 95% CI: 961–7,008). This study supports the potential of using UAS for marine mammal abundance studies. Significant hurdles to use of UAV for marine mammal surveys are aviation permits and the need for improved, commercially available, automated detection software as manual analysis of large number of images is prohibitively slow and expensive. Despite these hurdles the concept of using of UAV for aerial marine mammal surveys has significant potential.

In Chapter 4, spatial use of summer feeding grounds of Sakhalin, Russia, by western North-Pacific gray whales (WNP) was defined based on a 13-year long photo-identification dataset. This study is part of a joint monitoring Program that started in 2002 and consisted of studies on distribution, prey availability, acoustics, photo identification and behavior. It was established by two E&P operators (Sakhalin Energy Investment Company Inc. and Exxon Neftegas Ltd.) because of concerns of development activities in the near vicinity of the only known summer feeding area of WNP gray whales. The WNP gray whale feeding grounds are off the northeastern coast of Sakhalin Island, Russia and is comprised of a nearshore and offshore component that can be distinguished by both depth and location. Spatial movements of gray whales within their foraging grounds were examined based on 13 years of opportunistic vessel and shore-based photo-identification surveys. Site fidelity was assessed by examining annual return and resighting rates. Lagged Identification Rates (LIR) analyses were conducted to estimate the residency and transitional movement patterns within the two components of their feeding grounds. In total 243 individuals were identified from 2002-2014, among these were 94 calves. The annual return rate over the period 2002-2014 was 72%, excluding 35 calves only seen one year. Approximately 20% of the individuals identified from 2002-2010 were seen every year after their initial sighting (including eight individuals that returned for 13 consecutive years). The majority (239) of the

WNP whales were observed in the nearshore area while only half (122) were found in the deeper offshore area. Within a foraging season, there was a significantly higher probability of gray whales moving from the nearshore to the offshore area. No mother-calf pairs, calves or yearlings were observed in the offshore area, which was increasingly used by mature animals. The annual return rates, and population growth rates that are primarily a result of calf production with little evidence of immigration, suggest that this population is demographically self-contained and that both the nearshore and offshore Sakhalin feeding grounds are critically important areas for their summer annual foraging activities. The nearshore habitat is also important for mother-calf pairs, younger individuals, and recently weaned calves. Nearshore feeding could also be energetically less costly compared to foraging in the deeper offshore habitat and provide more protection from predators, such as killer whales. The combination of (i) high site fidelity of WNP gray whales to the nearshore and offshore feeding ground, (2) absence of other known feeding areas in the Sea of Okhotsk, and (3) the relatively small spatial area of the nearshore and offshore feeding areas, makes the WNP population more susceptible to environmental changes and/or anthropogenic disturbance such as ice-coverage, fisheries or oil & gas development. Despite these factors this WNP gray whale population has seen an average growth rate of 4.3% between 2005 and 2015, but warrants continued focus to ensure this upward trend continues.

Off Sakhalin, a greater understanding of WNP gray whales' utilization, movement and site fidelity within their foraging habitat can benefit the development of new, or adjustment of existing, conservation management efforts of this population. Chapter 5 describes one of the most extensive and sophisticated monitoring and mitigation programs ever designed to avoid and minimize the potential impacts of a 4D seismic survey on this population of WNP gray whales. To minimize disruptions to the whales' feeding activity and enhance understanding of the potential impacts of seismic surveys on WNP gray whales, an extensive monitoring and mitigation plan (MMP) was developed. Typically, mitigation plans involve observers on seismic vessels to monitor for the presence of marine mammals in an exclusion zone to prevent physical injury to the animals. Due to the protected status of western gray whales, an additional protection zone based on a behavioural disturbance threshold of exposure of 156 dB re $\mu\text{Pa}^2\text{-s}$ per pulse was applied for whales within their feeding habitat defined by the estimated 95% abundance contour. Real-time radio-transmitting acoustic recorders were deployed along this contour to verify modelled acoustic footprints within the feeding grounds. Shore- and vessel-based observation teams monitored for the presence and activity of whales. A real-time GIS workflow tracking procedure was developed that integrated acoustic and whale positioning data to determine if sound levels at a whale's position within the feeding area exceeded the behavioural threshold. In that case a shut-down of the seismic source was implemented. Additionally, behaviour and distribution surveys were conducted before, during and after the seismic survey to evaluate the effectiveness of the MMP. No large changes in whale movement, respiration, or distribution patterns were observed during the seismic survey. This could be interpreted to mean that the MMP was effective in reducing the sound exposure and behavioural responses of gray whales to seismic sounds. Development of this

specific MMP far exceeded the standard measures applied to seismic surveys. Implementation of this MMP was logistically and technically challenging. Costs associated with planning and implementation of this MMP were therefore also significantly higher compared to most MMPs. Due to the small population of North Pacific gray whales and proximity to their feeding grounds these additional efforts were considered necessary by the operating company Sakhalin Energy Investment Company Ltd.

In chapter 6 the results of a passive acoustic monitoring (PAM) program are presented around an extensive seismic program, involving four vessels, conducted in 2012, in Baffin Bay, west Greenland. This program included measurement of ambient sound levels in 2013 and 2014. Long-distance (~150 km) pre-survey acoustic modeling was performed in accordance with regulatory requirements. Four acoustic recorders, three with hydrophones at 100, 200, and 400 m depths, measured ambient and anthropogenic sound during the survey. Additional recordings without the surveys were made from September 2013 to September 2014. The results showed that 1) the soundscape of Baffin Bay is typical for open ocean environments and Melville Bay's soundscape is dominated by glacial ice noise; 2) there were distinct multipath arrivals of seismic pulses 40 km from the array; 3) seismic sound levels varied little as a function of depth; 4) high fidelity pre-survey acoustic propagation modeling produced reliable results; 5) the daily SEL did not exceed regulatory thresholds and were different using Southall *et al.* (2007) or NOAA weightings (NMFS 2016); and 6) the survey increased the 1-min SPL by 28 dB, with most of the energy below 100 Hz; energy in the 16000 Hz octave band was 20 dB above the ambient background 6 km from the source. This study provided a wealth of information on the natural soundscape of Baffin and Melville Bay, as well as on the contribution of seismic surveys to that sound scape. Key results were the quantification of the seismic acoustic footprint and the finding that long-range sound propagation modeling studies can be accurate but rely on the availability of high-fidelity environmental model input data.

The passive acoustic monitoring program described in chapter 6 was augmented with more recorders in Baffin and Melville Bay to detect vocalizing marine mammals in these areas, which is the main topic of chapter 7. Because of the expansion of hydrocarbon exploration in northwest Greenland it was deemed increasingly important to understand the occurrence of marine mammals in the region. In this chapter the seasonal and spatial call occurrence of marine mammals in Baffin Bay and Melville Bay are described. Four Autonomous Multichannel Acoustic Recorders (AMARs) were deployed during summer 2012 (late July to early October), five recorders during September 2013, and two recorders were deployed year-round in 2013–2014 (late September 2013 to early September 2014). Species' call presence was analysed using automatic call detection and manual verification analysis methods. Narwhal calls were detected in spring and fall, showing a south-north migration pattern in spring and a north-south migration pattern in fall. Few beluga whales were detected during fall 2013 and spring 2014. Bearded seal (*Erignathus barbatus*) calls were detected mainly during spring (mating period). A small

number of bowhead whale calls (*Balaena mysticetus*) were detected during fall 2013 and spring and summer 2014. For the first time at this latitude in the western Arctic Ocean, long-finned pilot whales (*Globicephala melas*) and sperm whales (*Physeter macrocephalus*) were detected during summer and fall. Our results suggest that the presence of marine mammals in Baffin Bay and Melville Bay is mainly governed by the annual cycle of sea ice formation and decay. This study is a good example of an inaccessible Arctic winter area resulting in relative paucity of marine mammal sighting data in Baffin Bay in this period. PAM proved to be useful tool to learn about the seasonal and interannual movements of marine mammals in this remote area. Observations on species occurrence obtained during this year-round data collection effort would have helped gauge the management (mitigation) efforts needed in this area should further hydrocarbon development in this area have taken place.

Chapter 8 provides the results of an acoustic monitoring study of sound levels associated with arctic exploratory drilling activities. In this chapter underwater sound levels are characterized that are produced by three different drilling units during offshore exploration drilling at three sites in the Beaufort and Chukchi seas in 2013 and 2015. Received levels and spectra are reported as functions of distance from each operation during drilling and excavation of mudline cellars (MLCs). Sound levels emitted during MLC excavation exceeded those during drilling at all three sites, although this operation was much shorter in duration. Drilling sounds exhibited tones below 2 kHz, with harmonics present to 10 kHz, while MLC excavation sounds were broadband in character. Drilling sounds varied substantially between the three operations, whereas, MLC excavation sounds were more consistent in amplitude and spectral distribution. Estimates of broadband and 1/3-octave band source levels were computed from measurements at 1 kilometer range. The broadband drilling source levels were 168.6 dB re 1 $\mu\text{Pa}\cdot\text{m}$ for the *Kulluk* drilling unit, 174.9 dB re 1 $\mu\text{Pa}\cdot\text{m}$ for the drillship *Noble Discoverer*, and 170.1 dB re 1 $\mu\text{Pa}\cdot\text{m}$ for the semi-submersible *Polar Pioneer*. The spectral characteristics of drilling sounds had spectral maxima between 50 and 300 Hz, with decreasing spectral density levels above 300 Hz. These source levels are typically lower than those for large commercial vessels (containerships, bulk carriers, vehicle carriers, cargo ships, and tankers) operating at normal operating speeds, that can range between 177 and 188 dB re 1 $\mu\text{Pa}\cdot\text{m}$. The received levels measured at 1 km during MLC excavation yielded source level estimates that were more consistent among the sources: 191.8 dB re 1 μPa , 193.0 dB re 1 μPa , and 193.3 dB re 1 μPa for the *Discoverer*, *Kulluk*, and *Polar Pioneer*, respectively. These sound levels were more broadband in nature with higher frequencies compared to drilling.

Finally, in chapter 9 several conclusions and recommendations are provided based on the studies presented in this dissertation. These recommendations contribute to the overall purpose of this program, which was to advance the protection of marine mammals during the implementation of modern E&P activities through a number of themes such as risk management, efficacy of mitigation, monitoring technologies, monitoring and mitigation planning and measurement of unassessed E&P activities. The chapters in this thesis cover a wide range of different topics,

some of which may not appear to be directly related. Nevertheless, all the chapters in this thesis contribute to one or more of these themes, and thus to the overall purpose of conducting executing E&P activities that are protective of marine mammal populations. Over the past decade a wealth of new insights on the effects of E&P activities on marine mammal populations has been obtained, resulting in better risk assessments and regulations. These projects may have made a small contribution to that increased understanding. However, with the expansion in focus on different species groups, sources and effects types, there is no room for complacency. To ensure co-existence between marine mammal and anthropogenic presence in offshore environments, there is an ongoing need for studies and monitoring and mitigation programs.

Samenvatting

Offshore Exploratie en Productie (E&P) activiteiten, zoals seismisch onderzoek en olie- en gasboringen genereren geluid dat zich uitstekend voortplant in een mariene omgeving. Zeezoogdierenpopulaties in verschillende stadia van hun levenscyclus kunnen met deze activiteiten overlappen. Afhankelijk van het geluidsniveau, de frequentie en de duur van blootstelling aan geluid, kunnen zeezoogdieren door deze geluidsbronnen worden beïnvloed. Blootstelling van zeezoogdieren aan geluid op verschillende afstanden van een geluidsbron kan leiden tot verschillende effecten, variërend van gehoorschade (d.w.z. permanente gehoordrempelverschuiving), tijdelijke gehoordrempelverschuiving, tot gedragsveranderingen en/of verstoring, en maskering van akoestische communicatie. Als deze geluidseffecten ernstig zijn, voor langere tijd plaatsvinden, en er niet voldoende beperkende maatregelen worden toegepast, kunnen ze van invloed zijn op zeezoogdier populaties.

Om de risico's van onderwater geluid op zeezoogdieren te kunnen beoordelen kan het bron-pad-receptor model worden gebruikt. Hier is de volgende informatie voor nodig i) de akoestische kenmerken van de *bron*, zoals het geluidsniveau, frequentiespectrum en de duur van het geluid, ii) het *pad*, d.w.z. de manier waarop geluid zich door de waterkolom voortplant, en wordt beïnvloed door omgeving en fysieke omstandigheden (zoals water temperatuur en bathymetrie) (iii) karakteristieken van *receptoren* zoals bijvoorbeeld de verspreiding en grootte van een populatie en de daar bijhorende seizoensgebonden variatie, soort-specifieke audiogrammen, tijdelijke gehoordrempelverschuivingsgrenzen, soort-specifieke gevoeligheid voor verstoring, enz.

In hoofdstuk 2 wordt ter introductie van dit onderwerp een overzicht gegeven van de effecten die E&P-geluidsbronnen op zeezoogdieren kunnen hebben en de mitigerende maatregelen die kunnen worden toegepast om deze effecten te beperken. In dit hoofdstuk wordt het bron-pad-receptor model toegepast om de huidige kennis samen te vatten omtrent 1) E&P impulsieve geluidsbronnen zoals air gun arrays en continue geluidsbronnen zoals boringen (bron), 2) hoe geluid dat gegenereerd wordt door deze bronnen zich door de waterkolom voortplant (pad) en, 3) de effecten van deze geluiden op zeezoogdieren (receptor). Mogelijke ongemitigeerde effecten van E&P-activiteiten op zeezoogdieren kunnen worden ingedeeld op basis van hun effect en de ruimtelijke schaal waarop ze plaats kunnen vinden. Dit kan variëren van ernstige effecten op een kleinere ruimtelijke schaal tot minder ingrijpende effecten die zich binnen een groter gebied voor kunnen doen (meestal, maar niet altijd, in de volgende volgorde: permanente gehoordrempelverschuiving → tijdelijke gehoordrempelverschuiving → gedragsstoornissen → maskeren). Deze effecten kunnen variëren van kleine gedragsverandering binnen een enkel individu tot significant populatie veranderingen. Beschikbare monitoringstechnieken, die toegepast kunnen worden om onze kennis van de effecten van E&P- activiteiten op zeezoogdieren te verbeteren worden ook in dit hoofdstuk beschreven aan de hand van het bron-pad-receptor model. Daarnaast wordt een overzicht gegeven van mitigerende maatregelen die in de E&P-

industrie worden toegepast om onaanvaardbare effecten op zeezoogdieren te voorkomen. Deze maatregelen kunnen worden ingedeeld volgens de mitigatiehiërarchie (vermijden > minimaliseren > herstel > compensatie). Ten slotte wordt in dit hoofdstuk gepleit voor het toepassen van het ALARP-principe (As Low As Reasonably Practical) in (inter)nationale richtlijnen voor het toepassen van mitigerende maatregelen tijdens E&P-activiteiten. Hiermee wordt bedoeld dat de toegepaste mitigerende maatregelen in E&P-activiteiten evenredig moeten zijn met het geraamde risico op zeezoogdierenpopulaties en redelijkerwijs haalbaar moeten zijn.

In hoofdstuk 3 wordt een studie beschreven over de schatting van de populatiegrootte van een narwal populatie in Melville Bay, Groenland, gebaseerd op vliegtuigtellingen. In deze studie wordt een vergelijking gemaakt tussen een 'double observer line-transect' (MRDS) survey, met vier menselijke waarnemers, met een strip survey, waarbij een fotocamerasysteem werd gebruikt. Het doel van de studie was om te bepalen of camerasystemen uitgerust op 'Unmanned Aerial Systems' (UAS) vergelijkbare schattingen van populatiegrootte kunnen geven als wanneer menselijke waarnemers in vliegtuigtellingen worden gebruikt. Dit is de eerste gepubliceerde studie waarin een vergelijking wordt gemaakt van een geschatte zeezoogdier populatie die wordt bepaald door zowel digitale foto's als door menselijke waarnemers. Van 25 tot en met 30 augustus 2014 werd een MRDS gehouden boven Melville Bay. In dit gebied komt een van de twee narwal (*Monodon monoceros*) populaties in West Groenland voor. Tijdens de vliegtuigtelling werd 1.932 kilometers afgelegd langs 33 van tevoren ontworpen transecten, waarbij het zeeoppervlak werd geobserveerd voor de aanwezigheid van narwal door 4 waarnemers. Daarnaast was het vliegtuig ook uitgerust met twee camera's die aan beiden kanten van de vluchtlijn elke drie seconden foto's van het wateroppervlak maakte. Analisten bestudeerden alle beelden voor de aanwezigheid van narwal en deze observaties werden vervolgens vergeleken met die van de waarnemer. Een ander doel van deze studie was om te bepalen wat de voor- en nadelen waren van beide methodes. Na correctie voor de maximale detectieafstand van de foto's (500 m) hadden de beeldanalisten meer waarnemingen (62) en een lagere gemiddelde groepsgrootte (2,2) in vergelijking met de waarnemers (36 en 3,5, respectievelijk), wat resulteerde in vergelijkbare aantallen individuen die door beide platforms werden gedetecteerd (135 vs. 126). De geschatte populatiegrootte op basis van de beeldwaarnemingen was 2.536 (CV=0,51, 95% BI: 1.003-6.406), wat niet significant verschilde van de schatting van 2.596 individuen door de waarnemers (CV = 0,51; 95% BI: 961-7.008). Deze studie bevestigt het potentieel van het gebruik van UAS voor zeezoogdieren populatie studies. Belangrijke obstakels voor het gebruik van UAS voor zeezoogdieronderzoek zijn de luchtvaart vergunningen en de noodzaak voor verbeterde, commercieel beschikbare, geautomatiseerde detectie software. De analyse van grote hoeveelheden foto's door analisten is bijzonder arbeidsintensief, traag en kostbaar. Ondanks deze moeilijkheden toont deze studie aan dat het concept van het gebruik van UAS voor het bepalen van de populatiegrootte van zeezoogdieren een aanzienlijk potentieel heeft.

In hoofdstuk 4 wordt het ruimtelijk gebruik van de zomer foerageergronden bij Sakhalin, Rusland, door de western North-Pacific (WNP) grijze walvis beschreven, op basis van een 13 jaar lange foto-identificatie studie. Deze studie is onderdeel van een groter onderzoeksprogramma, het 'Joint Monitoring Program' dat al sinds 2002 plaatsvindt. Naast foto-identificatie bestaat dit programma uit verspreiding, voedselbeschikbaarheid, akoestiek en gedragsstudies. Dit onderzoeksprogramma wordt uitgevoerd door twee E&P-bedrijven (Sakhalin Energy Investment Company Inc. and Exxon Neftegas Ltd.) vanwege zorgen over E&P-ontwikkelingsactiviteiten vlakbij het enige bekende zomervoedergebied van WNP-grijze walvissen. De foerageergronden van de WNP grijze walvis bevinden zich voor de noordoostelijke kust van Sakhalin, Rusland en bestaat uit een 'nearshore' en 'offshore' component die verschillen in locatie en waterdiepte. De ruimtelijke bewegingen van WNP grijze walvissen binnen hun foerageergronden werden onderzocht op basis van een 13 jaar lang foto-identificatie onderzoek, waarbij observaties zijn gedaan vanaf zowel vaartuigen en de kust. Plaatstrouw werd bepaald door het jaarlijkse terugkeerpercentage en de 'resighting rate'. 'Lagged Identification Rates' (LIR) analyses zijn uitgevoerd om de residentie duur en bewegingspatronen tussen de 'nearshore' en 'offshore' foerageergronden te bepalen. Tussen 2002 en 2014 zijn in totaal 243 individuen geïdentificeerd, waaronder 94 kalveren. Het jaarlijkse terugkeerpercentage over de periode 2002-2014 bedroeg 72%, exclusief 35 kalveren die slechts gedurende één jaar werden geobserveerd. Ongeveer 20% van de geïdentificeerde individuen uit 2002-2010 werden elk jaar teruggezien na hun eerste waarneming (waaronder acht individuen die dertien opeenvolgende jaren terugkeerden). De meerderheid (239) van de WNP grijze walvissen zijn waargenomen in het 'nearshore' foerageergebied, terwijl slechts de helft (122) werden aangetroffen in het diepere 'offshore' foerageergebied. Tijdens een foerageerseizoen was er een aanzienlijk hogere kans dat individuen zich verplaatsten van het 'nearshore' naar het 'offshore' gebied, in plaats van andersom. Er zijn geen moeder-kalf paren, kalveren of jaarlingen waargenomen in het 'offshore' gebied. Dit 'offshore' gebied werd steeds vaker gebruikt naarmate individuen ouder werden. De jaarlijkse terugkeerpercentages, en de populatiegroei die voornamelijk het gevolg is geboorte van kalveren met weinig bewijs van immigratie, suggereren dat dit een zelfstandige populatie is en dat zowel de 'nearshore' en 'offshore' Sakhalin foerageergebieden van cruciaal belang zijn voor de zomer foerageer activiteiten van de WNP grijze walvis. Het 'nearshore' foerageergebied is voornamelijk belangrijk voor moeder-kalf paren, onlangs gespeende kalveren en jongere individuen. Mogelijke verklaringen hiervoor zijn dat foerageren in het 'nearshore' gebied energetisch minder intensief kan zijn in vergelijking met het diepere offshore gebied, en meer bescherming kan bieden aan roofdieren, zoals orka's (*Orcinus orca*). De WNP grijze walvispopulatie is vatbaar voor omgevingsveranderingen en/of antropogene verstoring zoals ijsdekking, visserij of olie & gasontwikkeling door een combinatie van factoren zoals (1) sterke plaatstrouw van WNP grijze walvissen aan de 'nearshore' en 'offshore' foerageergebieden, (2) afwezigheid van andere bekende foerageergebieden in de Zee van Ochotsk, en (3) het relatief kleine gebied van de 'nearshore' en 'offshore' foerageergebieden. Ondanks deze factoren is het aantal individuen in deze WNP grijze walvispopulatie tussen 2005 en 2015 toegenomen met een gemiddelde groei van 4,3%. Om er

zeker van te zijn dat deze opwaartse trend zich voortzet is voortdurende aandacht voor het welzijn van deze populatie echter gerechtvaardigd,

Een beter begrip van het gebruik, plaatstrouw, en de bewegingen tussen foerageergebieden van WNP grijze walvissen voor de kust van Sakhalin kan gebruikt worden voor de ontwikkeling van beschermingsmaatregelen die moeten leiden tot de instandhouding van deze populatie. Hoofdstuk 5 beschrijft een van de meest omvangrijkste en meest geavanceerde monitoring en mitigatie programma's die ooit zijn ontworpen binnen de seismische industrie. Dit programma werd ontwikkeld om de potentiële effecten van een 4D- seismische onderzoek op deze populatie van WNP grijze walvissen te voorkomen en/of te minimaliseren. Om verstoringen van de foerageeractiviteit van deze walvissen te mitigeren, en om meer inzicht te verkrijgen in de effecten van seismische onderzoeken op WNP-grijze walvissen, werd een uitgebreid monitoring- en mitigatieplan (MMP) ontwikkeld. Het is een vrij gebruikelijke mitigatietechniek dat waarnemers op seismische vaartuigen een uitsluitingszone controleren op de aanwezigheid van zeezoogdieren om gehoorschade bij deze dieren te voorkomen. Vanwege de beschermde status van WNP-grijze walvissen werd daarnaast ook een extra beschermingszone toegepast op basis van een drempelwaarde voor gedragsverandering van 156 dB re $\mu\text{Pa}^2\text{-s}$ per puls voor walvissen binnen hun foerageergebied. Dit gebied was gedefinieerd door de geschatte 95% populatie contour. Real-time radio-telemetered akoestische recorders werden gepositioneerd langs deze contour om gemodelleerde geluidswaarden binnen de foerageergronden te verifiëren. Observatieteams op land en op verschillende schepen observeerde het wateroppervlak op de aanwezigheid en het gedrag van grijze walvissen. Een real-time GIS-tracking procedure was ontwikkeld waarbij geverifieerde geluidswaarden en positioneringsgegevens van walvissen geïntegreerd werden. Dit systeem werd gebruikt om te bepalen of het geluidsniveau op de positie van een walvis die zich binnen het foerageergebied bevond, de geluidsdrempel voor gedragsverandering overschreed. Wanneer dat gebeurde werd de seismische bron stopgezet om gedragsveranderingen te voorkomen. Daarnaast werden voor, tijdens en na het seismisch onderzoek gedrags- en verspreiding surveys uitgevoerd om de effectiviteit van het MMP te evalueren. Er werden geen grote veranderingen in walvisbeweging, ademhaling, of verspreidingspatronen waargenomen tijdens het seismische onderzoek. Dit kan betekenen dat het MMP inderdaad effectief was in het verminderen van de geluidsblootstelling en de bijhorende gedragsreacties van grijze walvissen op seismisch geluid. De ontwikkeling en implementatie van dit specifieke MMP overtrof de standaard maatregelen die worden toegepast bij seismische onderzoeken. De implementatie van dit MMP was echter gecompliceerd vanuit een logistiek en technisch oogpunt. De kosten die de planning en uitvoering van dit MMP met zich meebrachten waren daarom ook aanzienlijk hoger in vergelijking met de meeste standaard MMP's. Vanwege de kleine populatie en beschermde status van WNP grijze walvissen en de nabijheid van hun foerageergebieden ten opzichte van het seismisch onderzoek werden deze extra maatregelen noodzakelijk geacht door de uitvoerder Sakhalin Energy Investment Company Ltd.

In hoofdstuk 6 worden de resultaten van een passief akoestisch monitoring (PAM) programma tijdens een uitgebreid seismisch onderzoek beschreven. Dit onderzoek werd uitgevoerd door vier schepen in Baffin Bay, West-Groenland, in 2012. Dit programma omvatte ook het meten van de natuurlijke geluidsniveaus in 2013 en 2014. Een lange afstand (~ 150 km) pre-survey akoestische modelleringstudie werd uitgevoerd in overeenstemming met de wettelijke voorschriften. Door middel van vier akoestische recorders, drie met hydrofoons op 100, 200 en 400 m diepte, en één recorder in de nabijgelegen Melville Bay, werden zowel natuurlijke en antropogene geluidsniveaus gemeten tijdens voor en tijdens het seismisch onderzoek. Van september 2013 tot september 2014 werden aanvullende metingen aan natuurlijke geluidsniveaus verricht toen er geen seismisch onderzoek plaatsvond. De resultaten van deze studie toonden aan dat 1) het geluidslandschap van Baffin Bay typisch was voor een open oceaan omgeving en Melville Bay's geluidslandschap werd gedomineerd door geluid van gletsjers; 2) er verschillende multipath aankomsten van seismische pulsen waren op 40 km van de seismische bron; 3) seismische geluidsniveaus weinig varieerde als een functie van diepte; 4) high-fidelity pre-survey akoestische propagatie modellering studies resulteerde in betrouwbare resultaten; 5) de dagelijkse SEL-levels binnen de wettelijke drempels bleven en verschilde afhankelijk van de toepassing van Southall *et al.* (2007) of NOAA wegingen (NMFS 2016); en 6) het seismische onderzoek het 1-min geluidsdruk niveau (SPL) met 28 dB verhoogde, waarvan het grootste deel van de energie zich onder de 100 Hz bevond, energie in de 16kHz octaaf band was 20 dB boven het natuurlijke omgevingsgeluidsniveau op 6 km afstand van de seismische bron. Deze studie leverde grote hoeveelheid aan informatie op over het geluidslandschap van Baffin en Melville Bay, evenals over de verandering van het geluidslandschap dat veroorzaakt wordt door seismische onderzoeken. Andere belangrijke resultaten waren de kwantificering van de seismische geluidsdruk niveaus en de bevinding dat lange afstand geluidsvoortplantingsmodellering studies nauwkeurig kunnen zijn, maar afhankelijk zijn van de beschikbaarheid van high-fidelity gegevens die nodig zijn voor de parameterisatie van de geluidsvoortplantingsmodellen.

Het passieve akoestische monitoring (PAM) programma beschreven in hoofdstuk 6 werd uitgebreid met meer recorders in Baffin en Melville Bay om vocaliserende zeezoogdieren in deze gebieden te detecteren (hoofdstuk 7). Vanwege de mogelijke olie- en gasontwikkeling in het noordwesten van Groenland was het noodzakelijk om de aanwezigheid en verspreiding van zeezoogdieren in deze regio beter te begrijpen. In dit hoofdstuk worden de seizoensgebonden en ruimtelijke vocalisatie patronen van zeezoogdieren in Baffin Bay en Melville Bay beschreven. In de zomer van 2012 (eind juli tot begin oktober) werden vier autonome multichannel akoestische recorders (AMARs) ingezet, in September 2013 werden 5 recorders ingezet en twee recorders werden ingezet van september 2013 tot begin september 2014. Vocalisaties van verschillende zeezoogdier soorten op de geluidsoptnamen werden geanalyseerd met behulp van automatische methoden voor vocalisatie-detectie en handmatige verificatie van deze analyses. Bevindingen waren dat narwal-vocalisaties aanwezig waren in het voorjaar en de herfst, tijdens de zuid-noord migratie in het voorjaar en de noord-zuid migratie in de herfst. In de herfst van 2013 en het

voorjaar van 2014 werd een klein aantal belugawalvissen (*Delphinapterus leucas*) aangetroffen. Baardrob (*Erignathus barbatus*) oproepen werden vooral ontdekt tijdens de lente (paringsperiode). Een klein aantal Groenlandse walvis (*Balaena mysticetus*) vocalisaties werden ontdekt in de herfst van 2013 en de lente en zomer van 2014. Voor het eerst werden op deze breedtegraad in de westelijke Noordelijke IJszee grienden (*Globicephala melas*) en potvissen (*Physeter macrocephalus*) in de zomer en herfst ontdekt. Deze resultaten suggereren dat de aanwezigheid van zeezoogdieren in Baffin Bay en Melville Bay voornamelijk wordt bepaald door de jaarlijkse cyclus van het bevriezen en het smelten van de zee in dit gebied. Melville en Baffin Bay zijn goede voorbeelden van een Arctisch gebied dat in de winter ontoegankelijk is, waardoor er over deze periode weinig zeezoogdierenwaarnemingsgegevens beschikbaar zijn. Deze studie bewees hoe nuttig PAM kan zijn om meer te weten te komen over het seizoensgebonden voorkomen van zeezoogdieren in afgelegen (arctische) gebied. Deze zeezoogdier waarnemingen, die plaatsvonden over meerdere jaren, zouden hebben bijgedragen aan betere beheersplannen, indien verdere ontwikkeling van olie en gas in dit gebied zou hebben plaatsgevonden.

In hoofdstuk 8 worden de resultaten van een akoestische monitoringstudie van de onderwatergeluidsniveaus van exploratiebooractiviteiten in de Beaufort en Chukchi zeeën weergegeven. Deze boringen werden uitgevoerd door drie verschillende boorplatformen tijdens proefboringen op drie locaties in de Beaufort en Chukchi zeeën in 2013 en 2015. Geluidsniveaus en spectra zijn weergegeven als functies van afstand tot elke operatie tijdens de proefboringen en het uitgraven van de Mudline Cellars (MLC's). De gemeten geluidsniveaus tijdens MLC-installatie waren luider dan de niveaus van de proefboringen op alle drie de locaties. MLC-installatie was echter veel korter in duur. De proefboringsspectra bevatten tonen van minder dan 2 kHz, met aanwezige 'harmonics' rond 10 kHz, terwijl MLC-graafgeluiden een meer breedband karakter hadden. Geluidsniveaus en spectra van de proefboringen varieerden aanzienlijk tussen de drie verschillende booroperaties, terwijl MLC-graafgeluiden consistentere waren in geluidsniveaus en spectrale distributie. De breedband en 1/3-octaf band bronniveaus (op 1 meter afstand van de bron) werden bepaald door terugpropagatie van geluidsmetingen op 1 kilometer afstand van de bron. De breedband bronniveaus van de boorschepen waren 168,6 dB re 1 $\mu\text{Pa}\cdot\text{m}$ voor het boorschip 'Kulluk', 174,9 dB re 1 $\mu\text{Pa}\cdot\text{m}$ voor het boorschip 'Noble Discoverer' en 170,1 dB re 1-m voor het halfafzinkbaar boorplatform Polar Pioneer. De spectrale kenmerken van de boorgeluiden hadden spectrale maxima tussen 50 en 300 Hz, met een afnemende spectrale dichtheid boven 300 Hz. Deze bronniveaus zijn doorgaans lager dan die voor grote commerciële schepen (containerschepen, bulkschepen, voertuigvervoerders, vrachtschepen en tankers) die met een normale snelheid varen, en die kunnen variëren tussen 177 en 188 dB re 1 $\mu\text{Pa}\cdot\text{m}$. De geluidsniveaus die werden gemeten op 1 km afstand van de MLC-installatie leverde geschatte bronniveaus op die meer consistent waren tussen de drie platformen: 191,8 dB re 1 $\mu\text{Pa}\cdot\text{m}$, 193,0 dB re 1 $\mu\text{Pa}\cdot\text{m}$, en 193,3 dB re 1 $\mu\text{Pa}\cdot\text{m}$ voor de Discoverer, Kulluk, en Polar Pioneer, respectievelijk. Deze geluidsniveaus hadden een meer breedband karakter en met hogere frequenties in vergelijking met proefboorgeluidsniveaus.

Tot slot worden in het laatste hoofdstuk verschillende conclusies en aanbevelingen gepresenteerd op basis van de verschillende studies in dit proefschrift. Deze aanbevelingen dragen bij aan het doel van dit promotieonderzoek, d.w.z. het beschermen van zeezoogdieren tijdens het uitvoeren van E&P-activiteiten door focus op een aantal thema's zoals risicomanagement, efficiëntie van mitigatiemaatregelen, monitoring technologieën, het plannen en uitvoeren van monitoring en mitigatiestrategieën, en metingen bij nieuwe activiteiten waar geen gegevens van beschikbaar zijn. In de afgelopen tien jaar is er een schat aan nieuwe inzichten verkregen over de effecten van E&P-activiteiten op zeezoogdierenpopulaties, wat heeft geleid tot betere risicobeoordeling en regelgeving. Ook deze studies in dit proefschrift hebben daaraan bijgedragen. Aangezien de zorgen over de effecten van geluid op verschillende diersoorten (bijvoorbeeld vis, crustaceën en zelfs plankton), van verschillende geluidsbronnen, en andere soorten effecten alleen maar toeneemt, is er nog meer werk te doen. Om er zeker van te zijn dat zeezoogdieren en antropogene activiteiten in een offshore omgeving samen kunnen bestaan, is er een blijvende behoefte aan nieuwe studies en innoverende monitoring en mitigatie programma's.

Acknowledgements

My father has always been an active supporter of my work, often encouraging me (in both subtle and not-so-subtle ways!) to think about starting a PhD program. The thought had been on the back of my mind for many years, but it was only during a run on a small deserted road in the Scottish Highlands in 2012 when the idea really solidified. I decided to leverage my work as an ecologist and marine mammal specialist with Sakhalin Energy and Shell, while gaining more in-depth research experience conducting work alongside our contracted external experts. I enquired with several universities in the UK and US but some of the requirements (i.e. course work, prelims) were not really an option for me, considering I was working a full-time job.

One sunny evening we were having drinks on the beach after a Shell environmental science workshop on Texel, the Netherlands, at the NIOZ facility (Royal Netherlands Institute for Sea Research) in 2014. During this social get-together I met Prof. Dr. Henk Brinkhuis (general director NIOZ) and we ended up talking about PhD opportunities in the Netherlands. Eventually he introduced me to Prof. Per Palsbøll of the Rijksuniversity Groningen and Dr. Kees Camphuysen of the NIOZ, which kick-started this endeavor. So, a first word of thanks to Prof. Dr. Brinkhuis for making these introductions and helping me take this first step towards this dissertation.

I was fortunate that Prof. Per Palsbøll accepted to be my promotor and Dr. Camphuysen agreed to be my co-promotor. At that time, Dr. Michael Macrander was the lead arctic environmental scientist in Shell and he was willing to be my supervisor. Per, I'm very thankful for your guidance, mentorship and flexibility over the last six years. Thanks to your flexible approach ('this is your PhD-program'), I managed to combine this effort with my other responsibilities. I regret that I didn't have more opportunities to visit your lab and have more personal interactions with you and your other students. Kees, I'm grateful for all your technical advice and critical review of my manuscripts, which greatly improved them. Michael, I've always enjoyed working with you during our arctic science days. Some of the arctic science programs that you initiated laid the foundation for studies presented in this dissertation. Thanks for your guidance and friendship throughout the years.

I would like to acknowledge the members of the assessment and PhD exam committees, Prof. Dr. Andy Read (Nicholas School of the Environment, Duke University), Prof. Dr. Ir. Jan Komdeur (Groningen Institute for Evolutionary Life Sciences, University of Groningen), Prof. Dr. Alex Aguilar (Department of Animal Biology – University of Barcelona) for their efforts in assessing this dissertation. I also thank Associate Prof. Dr. Laura Govers (Groningen Institute for Evolutionary Life Sciences - University of Groningen) and Associate Prof. Sancia van der Meij (Groningen Institute for Evolutionary Life Sciences - University of Groningen) for being part of the PhD exam committee.

A special word of appreciation to all my co-authors for their hard work, advice and enthusiasm on these research projects. I can't stress enough how critical you all have been in getting this dissertation over the finish line.

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I'd like to mention the continuous collaboration with JASCO Applied Sciences on numerous projects. Specifically I thank Roberto Racca, for fun times after countless Western Gray Whale Advisory Panel meetings all over the world, and for support during the 2010 Piltun-Astokh survey; Dave Hannay, for your excellent guidance on the Alaska program; Bruce Martin, for being an amazing acoustic advisor and for all your work on the Greenland acoustic data set - it was fun to see you progress and finalize your own PhD-program; Héloïse Frouin-Mouy, Marie-Noël Matthews and Jeff MacDonnell for managing the Greenland Baffin Bay PAM analysis; Stephen Turner, Eric Lumsden, and Scott Trivers for the successful and safe deployment and retrieval of the acoustic recorders in Baffin Bay; Melanie Austin, for taking a key role during the 2010 Sakhalin fieldwork and for leading the Alaska drilling source characterization effort; and the many others that have been involved in these projects.

The first publication in this dissertation involved the implementation of a complicated monitoring and mitigation plan around a seismic survey off Sakhalin, Russia in 2010. This program had a large onshore field component with acoustic, behavioral and distribution teams in the field. To say that the field camp was in a remote area is a bit of an understatement. The nearest villages, shops or paved roads were miles away. This meant we had to build a camp to house the ~40 researchers, field teams and support staff in the middle of nowhere. The plan involved shore and vessel-based teams and reliance on real-time acoustic measurements and communications between the different onshore and vessel-based teams. Managing these 24-hr operations and sometimes ordering the seismic vessel to shut-down was a challenging but rewarding experience.

I thank IUCN, and specifically Finn Larsen, the Seismic Survey Task Force, members of the WGWAP, and my Sakhalin Energy colleagues and contactors for their partnership in development of the Monitoring and Mitigation Plan which took about 2-3 years of preparations. This project would not have been possible without the tireless efforts of the distribution, behavioural and acoustic teams, Marine Mammal Observers, logistics teams and camp support staff. A big shout out to Peter van der Wolff, Igor Zhmaev and Roman Larin, who were working day and night to keep the camp running. I also want to thank Doug Bell for his mentorship and kindness. It was a pleasure to work with you and I'm grateful for all the flexibility you gave me during those years. I'm very proud of the 6 articles that were published on this program so thanks to the lead-authors Judy Muir, Glenn Gailey and Roberto Racca and many co-authors, for both your contributions in the field as well as for analyzing and publishing these results. Audrey, thank you for moving to Russia with me and enabling this opportunity.

Another program I was working on during my days with Sakhalin Energy Investment Company was the Joint Western Gray Whale Monitoring Program, which was executed jointly with Exxon Neftegas Limited. As part of this program, we implemented gray whale distribution, prey, behavioral and photo-identification and acoustic studies. I'd like to recognize Olga Tyurneva for her dedicated input to this program, Yuri Yakovlev for the countless hours of taking gray whale images, as well as the many other scientists involved in the joint program. Furthermore, a special word of thanks to Glenn Gailey for his leading role in improving the data management, useful lectures on whale biology and photo-identification, and unusually cheerful mood during the 2010 fieldwork. Entire soap series could be produced around the dynamics within the Joint Western Gray Whale Monitoring Program, but I'll limit it to expressing gratefulness to a few key folks – Mike Jenkerson, Lisanne Aerts, Doug Bell, Johan Pieters, Vladimir Efremov, Roman Larin, Igor Zhmaev, Brian Tibbles, Ingrid Rosenberger, Sandra Werner, Jennifer Dupont, Dorine Terwogt, Martin Boekholt, and many others. My special gratitude goes to Rodger Melton, the engineer turned biologist, for founding and providing much-needed leadership to the Joint Program. Sadly, Rodger passed away in 2017, but this ongoing multi-disciplinary research program is really his legacy.

After working for Sakhalin Energy Invest Company between 2006 and 2010 as biodiversity manager, I joined Shell Global Solutions in the role of environmental scientist. At that time Shell was actively focusing on Arctic exploration which landed me on the Greenland exploration project. Firstly, a word of acknowledgement to Brad Boschetto for getting me involved in this Greenland effort, for giving me the opportunity to participate in Baffin Bay fieldwork, and for being a fun-loving friend. The fieldwork in Baffin Bay was a memorable experience – to see those massive icebergs and the ways of living of local communities was impressive. As part of these arctic efforts, Shell was interested in developing Unmanned Aerial System technology for aerial marine mammal surveys. We had the opportunity to collaborate with the Greenland Bureau of Minerals and Petroleum who were conducting aerial narwhal surveys over Melville Bay, west Greenland. Mads-Peter Heide-Jørgensen and Rikke Hansen – thank you for letting us install a camera system on the aircraft, for your willingness to share data and results and for all your advice on this study. Bill Koski, a special word of thanks to you for all your expertise and help with getting the manuscript published. Other key people involved in this study were Kathleen Leonard (camera operation and project management), Dale Funk and Craig Reiser (camera installation), the pilots by Norlandair, aerial observers and image analysts.

The Baffin Bay exploration program involved a Passive Acoustic Monitoring and a Marine Mammal Observer program. Thanks to the Jasco engineering and field teams for developing and deploying the vertical moorings, the excellent crew of the M/V Arctic Hunter, and the marine mammal observer leads, Cecilia Vanman and Jan Durinck, and the many marine mammal observers involved in this project.

From 2013 onwards I was getting more involved in our Alaskan exploration project in the Chukchi and Beaufort seas – which was a massive undertaking from a technical, logistical, financial, permitting and stakeholder management point of view. The scale of the Passive Acoustic Monitoring program and marine mammal surveys were of a whole different level with dozens of deployed recorders and approximately 160 Protected Species Observers. The number of people involved in this program was enormous – too many to mention. Our Jasco friends did an excellent job in safely deploying and retrieving numerous acoustic recorders. Although not directly related to this dissertation, the experts and program managers at LGL and Greeneridge Sciences deserve recognition for their input to this program. I want to specifically thank Louis Brzuzy, who was leading the Alaska environmental monitoring program, for all his insightful advice, friendship and constructive input to this dissertation.

Over the years I've learned a lot about the effects of sound on marine life through active participation in the International Oil and Gas Producers' E&P Sound and Marine Life Joint Industry Programme. This group of company experts has been working together for over a decade to develop studies to fill key knowledge gaps. Almost all members are big characters, so meetings are always dynamic engagements. At least there is always time for a beer when the meetings are done. A personal highlight of the JIP programme for me was the organization of the ESOMM/JIP program review meeting in 2018 and the associated special edition of *Aquatic Mammals* for which I was guest-editor. Thanks to Frans-Peter Lam for giving me this opportunity.

In my role as an environmental scientist within Shell, I had the opportunity to work on numerous interesting projects and with various experts. There are too many different people to mention, but I want to give a shout out to all my PTS-E and Shell Renewables and Energy Solutions co-workers. I want to mention two of my closest ecologist partners in crime, Ray Valente and Steve Truchon. We are just devastated about the loss of Steve due to COVID early 2020 – Steve, you are missed. His legacy lives on in the sailing boat that Ray and I bought together and named after him.

On a more personal note, although I moved around quite a bit over the last two decades, I'm fortunate to still have close friends in the Netherlands/Europe. Okki, Yuri and Kjell – I hope we can all meet up in person later in 2021 for a beer or two.

I've been lucky to grow up in a supportive and warm family. I'm very thankful to Michiel and Mariette for being the best siblings possible. Mam, I couldn't wish for a more caring mom, thanks for all your love and support. Dad, thanks for all your encouragement, interest in this work and for always being there to help me.

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About the author

Koen Bröker was born on June, 18th, 1976, in Eindhoven, the Netherlands. In 1994 he began studying biology at the Utrecht University, with a marine biology program at the Rijksuniversiteit Groningen. During his studies he focused on both terrestrial and marine ecology. He graduated from this Msc program cum laude in 2000. From 2002-2006 he worked for Arcadis Euroconsult on a Coastal Resource Management Project with the Ministry of Fisheries in Sri Lanka. In 2006 he started to work for Sakhalin Energy Investment Company in Sakhalin, Russia, on the development of the Sakhalin-2 project that included development of the offshore Piltun-Astokh oil field and the Lunskeye natural gas field, and associated onshore infrastructure. From 2006-2010 he worked there as biodiversity manager which

included, amongst others, management of the western gray whale research program and served as company coordinator for the IUCN Western Gray Whale Advisory Panel (WGWAP). In 2010 he moved back to the Netherlands and started a position as environmental scientist with Shell Global Solutions. In this role he continued to support the western gray whale program as well as numerous E&P exploration and research projects aimed at studying and managing the effects of sound on marine life. In 2018 he joined Shell New Energies to manage the ecological impacts of offshore wind development. This scope expanded in 2019 when he took on the position of environmental manager for Shell Renewables and Energy Solutions, which involved management of environmental issues and risk. This new Shell line of business includes, amongst others, offshore and onshore wind development, solar power development, hydrogen and nature-based solutions, etc. In this role he is still involved in managing the effect of sound (i.e. through offshore pile-driving) on marine mammals. He started his PhD with Prof. Dr. Per J. Palsbøll at the University of Groningen in 2015 on the monitoring and mitigation of the effects of E&P sound on marine mammals and completed this program in 2021.

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