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Anthropogenic Noise in the Southern Ocean: an Update

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Preface

Questions regarding the impacts of underwater noise on Antarctic marine wildlife have been of interest to the CEP for more than two decades. SCAR has been an active participant and contributor to these discussions, first submitting a review of the state-of-knowledge to the Committee in 2000. Since that time SCAR has convened workshops and made further submission to the CEP (see ATCM41_ip028_e for details - https://documents.ats.aq/ATCM41/ip/ATCM41_ip028_e.doc)

More recently, in response to further requests from the CEP, SCAR initiated a comprehensive process to update the current state of knowledge on underwater noise.

This involved a number of steps, including:

- The coordination of an external review of literature by experts in the 2015/16 and 2017/18 intersessional periods on the issue of underwater anthropogenic noise, and the potential for impacts on and interactions with underwater sound and Antarctic marine wildlife.
- Convening an expert committee in late 2017 to provide further advice on this issue and bring all relevant information together to produce a Background and Working Paper.
- The expert committee was led by Professor Emeritus Mahlon C. "Chuck" Kennicutt II, past SCAR President (2008 to 2012), who oversaw the submission of the last SCAR update on this issue to the CEP in 2012. The committee members consisted of nine global experts (listed in the table below) with a diverse range of expertise and viewpoints.
- The first draft of the literature review was completed in early January 2018 and informed discussions within the expert committee. Further discussion and detailed input were facilitated by a questionnaire. The literature review and associated discussions focused on advances in knowledge since the 2012 update by SCAR to the CEP.

An Information Paper documenting progress was submitted to the CEP in 2018 (ATCM41_ip028_e - https://documents.ats.aq/ATCM41/ip/ATCM41_ip028_e.doc). The process culminated in two submissions to the 2019 CEP, the comprehensive Background Paper (ATCM XLII-CEP XXII BP003: Anthropogenic Noise in the Southern Ocean: an Update – https://documents.ats.aq/ATCM42/bp/ATCM42_bp003_e.doc – this SCAR Bulletin), which supported the Working Paper (WP 68 Anthropogenic Noise in the Southern Ocean: an Update - https://documents.ats.aq/ATCM42/wp/ATCM42_wp068_e.doc).

Anthropogenic sound in the Southern Ocean – Expert Committee Members

Member	Affiliation
Professor Mahlon C. "Chuck" Kennicutt II (Chair),	Professor Emeritus
Dr. Olaf Boebel	Alfred Wegener Institute, Germany
Professor Daniel C. Costa	University of California Santa Cruz, USA
Dr. Heike Herata	German Environment Agency, Germany, CEP Representative
Dr. Stephanie Langerock	Belgian Government, Belgian IWC, CCAMLR
Mirjam Müller	German Environment Agency, Germany
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Dr. Rachel Przeslawski	Geosciences Australia
Dr Michelle Rogan-Finnemore	Council of Managers of National Antarctic Programs
Professor Peter L. Tyack	University of St. Andrews, United Kingdom
Dr. Aleks Terauds (ex officio)	Chief Officer of SCAR-SCATS, Australia Antarctic Division
Professor Steven Chown (ex officio)	President of SCAR, Monash University, Australia

Anthropogenic Noise in the Southern Ocean: an Update[1]

This paper was submitted to CEP XXII (2019) as a Background Paper (ATCM XLII-CEP XXII BP003: *Anthropogenic Noise in the Southern Ocean: an Update*) in support of WP 68 *Anthropogenic Noise in the Southern Ocean: an Upd*ate, which summarised the findings of this paper. Both papers can be found at https://www.scar.org/antarctic-treaty/actm-papers/atcm-xlii-and-cep-xxii-2019-prague-czech-republic/

Summary[2]

This paper, and WP 68 which it supports, is provided in response to a request from CEP XVII (2014) that SCAR update information on anthropogenic sound in the Southern Ocean since SCAR's last update to ATCM XXXV-CEP XXV (Information Paper 21, 2012 - https://documents.ats.aq/ATCM35/ip/ATCM35_ip021_e.doc). Scientific knowledge regarding the effect of noise on marine wildlife continues to advance, based almost exclusively on studies outside the Antarctic region. Despite these advances in knowledge, the state-of-knowledge regarding the spatial and temporal distribution of sound sources, the real-world characteristics and distribution of anthropogenic noise and the environmental factors that determine its effects on receptor organisms and/or populations is judged by experts to be fair to good. How marine wildlife will respond to exposures to noise remains largely unknown with no

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[1] This paper utilizes the definitions established by the International Organization of Standards (ISO) 18405:2017 https://www.iso.org/standard/62406.html which defines terms and expressions used in the field of underwater acoustics, including natural, biological and anthropogenic (i.e. man-made) sound. In particular, the distinction between the usage of 'sound' and 'noise':

> **3.1.1.1 sound,** alteration in pressure, stress or material displacement propagated via the action of elastic stresses in an elastic medium and that involves local compression and expansion of the medium, or the superposition of such propagated alterations
>
> - Note 1 to entry: The medium in which the sound exists is often indicated by an appropriate adjective, e.g. airborne, water-borne, or structure-borne.
> - Note 2 to entry: In the remainder of this document, the medium is assumed to be a compressible fluid.
> - Note 3 to entry: A sound wave is a realization of sound.
> - Note 4 to entry: The word "sound" may also be used as part of a compound noun, in which case, it is a synonym of "acoustic". For example, "acoustic pressure" and "acoustic power"' are synonyms of sound pressure (3.1.2.1) and sound power (3.1.3.14).
>
> **3.1.1.2 ambient sound,** sound (3.1.1.1) that would be present in the absence of a specified activity
>
> - Note 1 to entry: Ambient sound is location-specific and time-specific.
> - Note 2 to entry: In the absence of a specified activity, all sound is ambient sound.
> - Note 3 to entry: Ambient sound includes ambient noise (3.1.5.11).
> - Note 4 to entry: Examples of specified activity include the act of measuring the underwater sound and the radiation of sound by specified sound sources.
> - Note 5 to entry: Ambient sound can be anthropogenic (e.g. shipping) or natural (e.g. wind, biota).
>
> **3.1.5.9 noise,** time-varying electric current, voltage, sound pressure (3.1.2.1), sound particle displacement (3.1.2.9), or other field quantity except the signal (3.1.5.8) or signals

[2] From ATCM XLI, IP XX (2017) - The focus of SCAR's review is anthropogenic noise. To any potential receiver (i.e., an individual of a species or a population) there are three categories of acoustic energy of interest: i) ambient sound, ii) biological sound – self-generated signals (e.g., vocalizations) or signals from potential predators or prey; and iii) noise - sound energy generated by human activities that is known to cause negative effects in the receiver. Noise as a term is ubiquitous in the scientific literature documenting the occurrence of impacts, or the lack thereof, in the presence of unwanted acoustic energy.

information for many important species. While there is improved knowledge of the effects of noise on several cetacean species, there remains a lack of research on marine species endemic to Antarctica, including little knowledge of population level effects and variations in effects with life stage. Due to the lack of fundamental knowledge, current approaches to mitigation and management remain largely unverified as to effectiveness in avoiding and/or reducing detrimental effects. Expanded monitoring of natural/ambient and anthropogenic sound in Antarctic marine environments is needed to fully assess real-world noise exposure scenarios. While at an early stage, identification of "sound-sensitive" Antarctic species, potential "sound hotspots" in Antarctica and cumulative effects are beginning to emerge. Further studies of the responses of Antarctic species and populations to anthropogenic noise are essential to advancing evidence-based policies that are practicable while achieving conservation goals. A description of the process followed to produce this paper is provided in ATCM XLI-CEP XXI Information Paper 28 (2018, https://documents.ats.aq/ATCM41/ip/ATCM41_ip028_e.doc).

Introduction[3]

In 2012, ATCM XXXV IP21 *Anthropogenic Sound in the Southern Ocean: an Update* (https://documents.ats.aq/ATCM35/ip/ATCM35_ip021_e.doc) identified a scientific synthesis of "The impacts of underwater noise on marine and coastal biodiversity and habitats", produced by the Subsidiary Body on Scientific and Technological Advice (SBSTTA) of the Convention on Biological Diversity (UNEP/CBD/SBSTTA/16/INF/12). Furthermore, ATCM XXXV IP21 recognized previous work by SCAR on the topic that included workshops by an Action Group convened in 2001, 2004 and 2006. Reports from these workshops were presented as ATCM XXV WP23 *Marine Acoustic Technology and the Environment*, ATCM XXVII IP78 *SCAR Report on Marine Acoustic Technology and the Antarctic Environment* (https://documents.ats.aq/ATCM25/wp/ATCM25_wp023_e.pdf), and ATCM XXIX WP41 *SCAR Report on Marine Acoustics and the Southern Ocean* (https://documents.ats.aq/ATCM29/wp/ATCM29_wp041_e.doc). These IPs and WPs summarized the status of scientific knowledge at the time of submission. A structure for a qualitative risk assessment of sound in Antarctic marine environments was among the outputs. The issue was further addressed in ATCM XXXIV WP38 *Antarctic Discussion Forum of Competent Authorities (DFCA) – Impacts of underwater sound to Antarctic waters* (https://documents.ats.aq/ATCM34/wp/ATCM34_wp038_e.doc). This preceding work remains relevant to ongoing discussions.

Between 2012 and 2018, activities related to sound in the marine environment have included reviews, conferences, workshops and research projects conducted by academia, industry and government. Outputs from these activities have been published in the peer-reviewed scientific and "grey" literature (usually not peer-reviewed). In adherence to SCAR quality assurance policies, peer-reviewed

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[3] From ATCM XLI, IP XX (2017) – "Experts advised SCAR that within the audiology and auditory physiology communities, noise is defined as "an aperiodic signal that interferes with the perception of sound…" For noise exposures a distinction is made between sound as a physical phenomenon and noise as an unwanted sound that is dependent upon the perception of a receiver. The anthropogenic sounds of interest to policy makers are the signals that are corruptive to ecological processes, communication, perception, and/or behaviour. Not all signals produced by human activities can be perceived by all species and responses are species and environmental setting specific. A signal is a sound that becomes noise only and when a receiver determines it to be disturbing, unwanted, or stressful.

publications are solely considered in this update. Publications prior to 2012 are considered part of the public record and are not repeated in this update.

Various aspects of anthropogenic sound in marine environments continued to receive attention in the scientific literature from 2012 to 2018. Several reviews during this time period examined sound sources and characteristics and the potential for impacts on marine wildlife. There has been progress on how to describe and measure acoustic environments in real-world scenarios. Evidence that anthropogenic noise can affect marine life continues to accumulate. Research aimed at improving assessments of the biological significance of observed responses to sound, and to better understand the potential for population level and cumulative impacts, has been conducted but much remains unknown.

A committee of experts was polled on the status of the issues considered in this paper as a first-step, qualitative assessment of the state-of-knowledge at the end of 2017 (Table 1).

Based on expert opinions, understanding of the sources and types of anthropogenic sound present in Antarctic marine waters is fair to good but often lacking completeness and important details. The state-of-knowledge of potential impacts for: 1) cetaceans (and marine mammals in general) is fair to good, 2) pinnipeds is poor to fair, 3) seabirds is poor, 4) fishes is fair and 5) invertebrates is poor – with a notable lack of knowledge about sounds' impacts on species endemic to the Antarctic region. The state-of-knowledge regarding the effectiveness of potential mitigation and management approaches is poor to fair with few studies quantifying the effectiveness of mitigation and/or management efforts in meeting conservation goals.

Summaries of peer-reviewed scientific literature that supports these conclusions are provided in this paper.

Table 1. Expert assessment of the state-of-knowledge of sound and its impact in Antarctic marine environments as of 2017*.

Expert	**1**	**2**	**3**	**4**	**5**	**6**
Sources and types of anthropogenic sound in the Antarctic	G	F	G	G	F	G
Studies that have investigated impacts of underwater sound – overall	F	NR	P	P-F	NR	P
Marine Mammals - Overall	F	G	F	P-F	F	F
Cetaceans	F	G	F	NR	G	G
Pinnipeds	F	NR	F	P-F	F	F
Seabirds	P	F	P	P	P	P
Fish	F	F	F	F	F	F
Invertebrates	P	F	P	P	NR	P
Mitigation and Management	P	F	P	P	NR	F

*Each category of knowledge was rated as: poor (P - red) - a critical lack of information, fair (F - yellow) – some knowledge but important information is lacking, good (G - blue) - a reasonable understanding of the issue exists but some important gaps remain, and very good/excellent (VG - green) - a level of knowledge sufficient to recommend policy actions. [NR- No Rating].

Sound in Antarctic Marine Environments

Sound in the ocean has two components: 1) natural ambient sound and 2) anthropogenic sound. In Antarctic marine environments there is significant spatial and temporal variability in natural underwater sound generated by winds, waves, ice interactions and organisms.

With the possible exception of some regions on the Antarctic Peninsula, sound-generating anthropogenic activity in Antarctic waters continues to be low compared with other oceanic regions. The levels and seasonal nature of human activities in the Antarctic region results in fewer anthropogenic sound sources being present than in other regions of the world's oceans. Fewer anthropogenic sound sources results in lower anthropogenic noise levels.

Natural Ambient Sound

The ocean is naturally replete with sound produced by wind, waves, rain, earthquakes, slope failure, fish calls, snapping shrimps and marine mammal signals.

Natural ambient sound in Antarctic marine environments is comparable to sound in other parts of the ocean with seasonal variations in sound indicating contributions from the fracturing, flexing and collision of sea ice. There is more spatial and seasonal variability in natural sounds in Antarctic waters than at lower latitudes due to the presence of and changes in ice in its many forms.

While a sound generator, sea ice can create quiet conditions due to the absence of surface waves, and affect sound propagation due to scattering effects from ice and absorption at the ice-water interface (Haver et al. 2017). Icebergs are an important natural source of sound, making both long-duration harmonic tremors when they shoal or collide with other icebergs, and broadband bursts when breaking-up in the open sea (Matsumoto et al. 2014; Dziak et al. 2015). The sounds from ice disintegration are a low frequency sound source in all southern hemisphere oceans, not just Antarctic waters (Matsumoto et al. 2014). The grounding of icebergs and associated scouring of the seabed are a natural source of sound. In many Antarctic marine environments, biological sounds, particularly those from baleen whales, can dominate certain frequencies for part of the year (Menze et al. 2017).

In regard to the transmission of sound, oceanographic conditions south of the Polar Front result in the sound speed minimum being close to the sea surface, creating a surface duct enhancing propagation of sound close to the surface. Although transmission loss is largely unaffected by ice coverage at ranges where direct path propagation is possible, it is greatly affected at distances in which the only propagation path requires at least one water-ice reflection (Roth et al. 2013).

The levels of natural ambient sound remain incompletely quantified in Antarctic marine environments. Expanded monitoring will be required to more completely establish the spatial and temporal variability of natural ambient sound in Antarctic marine environments.

Anthropogenic Sound

Sources of anthropogenic sound in the world's oceans that are found in Antarctic marine environments include ships, scientific seismic surveys and echosounders (for navigation, biomass estimation, current profiling, depth sounding, and sub-bottom *profiling). Anthropogenic sound source types and characteristics in the Antarctic are reasonably well known though spatial and temporal variability is not well characterized.*

Ships

While commercial shipping is a major source of sound in the world's oceans, the marine area below 60^0 S has no commercial shipping routes. The Antarctic Treaty prohibits activities of a military nature and the Environmental Protocol prohibits activities related to mineral-resource exploration or exploitation. A body of knowledge has accumulated about anthropogenic noise associated with military activities. Its relevance to Antarctica is questionable due to the lack of such activities in the region and the unique (power and frequency) characteristics of sound generated by these activities.

The numbers and density of ships navigating Antarctic waters is low compared with other regions of the world's ocean.

In Antarctica, ships are utilized for fishing, the transport of tourists, for scientific station resupply and provisioning and in support of a wide range of scientific activities.

Ships are used in Antarctic waters by commercial fisheries targeting Antarctic species such as krill, mackerel, icefish and Antarctic rock cod. As of March 2018, forty (40) fishing vessels had been authorized for the season 2017/2018 (CCAMLR). Sound sources may be aboard legal and illegal fishing vessels in certain regions of Antarctica.

Fishing activities in Antarctic waters are far lower than those conducted in other regions of the world's oceans

Antarctic tourist ship traffic is concentrated along the Antarctic Peninsula in the summer in areas where wildlife is expected, such as breeding sites for penguins, sea birds and seals (Bender et al. 2016). The International Association of Antarctica Tour Operators (IAATO) reported an increase in tourist voyages up to 2007/08, with subsequent numbers fluctuating between 200-300 voyages each season. The number of tourist voyages for the 2017/18 season was 348, which is the highest number yet recorded for a single season.

The locations and routes of ship voyages that support scientific activities, including resupply ships, oceanographic research vessels and deployment and installation of instruments, are known (e.g., via the Council of Managers of National Antarctic Programs' notifications). As of March 2018, the predicted number of research voyages for 2017/18 is a minimum of 133 to be undertaken by thirty-two (32) vessels. Resupply ship routes are well established. For most scientific cruises, tracks are available in near-real time or retrospectively from national operators. Icebreakers generate higher and more variable localized sound levels than other vessels, mainly as a result of propeller cavitation related to backing and ramming of ice and the sound from the breaking ice itself (Roth et al. 2013). Such vessels are often necessary to support science activities and scientific station resupply. Icebreakers tend to avoid ramming to save on fuel. Transducer-based equipment used aboard vessels operating in the Antarctic include echo-sounders (single- or multi-beam), side-scan sonars and sub-bottom profilers. The types of equipment used have been similar over the years, although frequency sweeps or 'chirps' using an FM pulse that cascade through a frequency range of several kHz have become more common. In addition, short-range communication devices (e.g. ROVs/AUVs, instrumented buoys/floats) are becoming increasingly frequent**.**

A more complete understanding of Antarctic regional sound sources related to ships must consider all types of ship activities and the sound producing sources they may carry that are known to cause disturbances.

Seismic Surveys

Seismic surveys in support of science have been acquired in the waters surrounding Antarctica for more than thirty-five (35) years (Breitzke 2014). Fifty-percent (50%) of these seismic surveys used relatively small air gun arrays with source levels 15-20 dB lower than those typically used in energy exploration. It is known where seismic surveys have been conducted but the detailed characteristics of these events are often not well documented and/or easily accessible. Jakobsson et al. (2016) describe a wide range of current sources used for seabed profiling, including some that are used in Antarctic marine environments at levels known to cause disturbance. Compared to seismic surveys that support energy exploration in other regions of the world's oceans; seismic survey density, frequency and noise levels are far lower in Antarctic waters.

Other Sound Generating Activities

Occasional construction activities at existing and/or new Antarctic bases can generate sound in coastal marine waters. While acute impacts have been attributed to the use of explosives and pile driving, these activities rarely occur in Antarctic marine environments and in most instances are one-time, localized events.

Marine Wildlife and Anthropogenic Sound

Since 2012, a number of reports have reviewed and updated the state-of-knowledge by species and types of sound in regard to the potential impacts of sound on marine life. Potential impacts of exposure to noise can range from chronic to acute including: 1) reduction in communication ranges and obscuring sounds of interest (masking), 2) disruption of reproductive behaviours affecting reproductive success, 3) disruption of energetic budgets, 4) exclusions of organisms and populations from important habitats, 5) inducement of chronic physiological stress responses, 6) temporary or permanent loss of hearing sensitivity, 7) physical injury and 8), in extreme cases, death. Most reviews summarize information from regions of the world's ocean other than Antarctica.

Variations in methodologies amongst studies make meaningful comparisons challenging. Some studies are based on laboratory or caged animal experiments, making translation of results to real-world sound exposure scenarios difficult. Therefore, caution should be used when extrapolating findings from other regions of the world's oceans and from laboratory-based exposures to Antarctic marine environments and species. However, there are studies reporting results from wild populations of animals that either occur or have closely related taxa occurring in Antarctic waters, therefore these studies are applicable.

Hearing Threshold Shifts in Marine Mammals

The effect of anthropogenic noise on the hearing of marine mammals has been demonstrated by measurement of Temporary Threshold Shift (TTS, Finneran 2015, NMFS 2016). In general, the state-of-knowledge of potential impacts of sound on the hearing of marine mammals is fair to good but highly variable among species. Intense sound and long-term chronic exposure is expected to lead to Permanent Threshold Shifts (PTS). These criteria are used to define safety zones around equipment based on source level. The development of PTS in terrestrial animals and humans is similar and influenced by a complex range of factors.

Exposure experiments with toothed whales and seals together with anatomical considerations suggest that the effects of noise on marine mammals follow patterns similar to those in terrestrial mammals, though understanding of the phenomena is incomplete. US Guidance for assessing the effects of anthropogenic underwater sound on the hearing of marine mammal species and identifying the received levels, or acoustic thresholds, at which individual marine mammals are predicted to experience changes in their hearing sensitivity (either temporary or permanent) was updated in 2016 (Tables 2 and 3; National Marine Fisheries Service [NMFS] 2016).

Table 2. Marine mammal hearing groups (NMFS 2016)

Hearing Group	Generalized Hearing Range*
Low-frequency(LF) cetaceans (baleen whales)	7 Hz to 35 kHz
Mid-frequency (MF) cetaceans (dolphins, toothed whales, beaked whales, bottlenose whales)	150 Hz to 160 kHz
High-frequency (HF) cetaceans (true porpoises, *Kogia*, river dolphins, cephalorhynchid, *Lagenorhynchus cruciger* & *L. australis*)	275 Hz to 160 kHz
Phocid pinnipeds (PW) (underwater) (true seals)	50 Hz to 86 kHz
Otariid pinnipeds (OW) (underwater) (sea lions and fur seals)	60 Hz to 39 kHz

* Represents the generalized hearing range for the entire group as a composite (i.e., all species within the group), where individual species' hearing ranges are typically not as broad. Generalized hearing range chosen based on ~65 dB threshold from normalized composite audiogram, with the exception for lower limits for LF cetaceans (Southall et al. 2007) and PW pinniped (approximation).

Table 3. Marine underwater mammal threshold shift studies 2012-2017 (modified from NMFS 2016)

References in Chronologic Order+	Sound Source (Sound Source Category)	Sound-Exposed Species (number of individuals^)
Kastelein et al. 2012a	Octave-band noise (non-impulsive)	Harbour seal (2)
Kastelein et al. 2012b	Octave-band noise (non-impulsive)	Harbour porpoise (1)
Finneran and Schlundt 2013	Tones (non-impulsive)	Bottlenose dolphin (2)
Popov et al. 2013	Half-octave band noise (non-impulsive)	Beluga (2)
Kastelein et al. 2013a	Octave-band noise (non-impulsive)	Harbour seal (1)

References in Chronologic Order+	Sound Source (Sound Source Category)	Sound-Exposed Species (number of individuals^)
Kastelein et al. 2013b	Tone (non-impulsive)	Harbour porpoise (1)
Popov et al. 2014	Half-octave band noise (non-impulsive)	Beluga (2)
Kastelein et al. 2014a	1-2 kHz sonar (non-impulsive)	Harbour porpoise (1)
Kastelein et al. 2014b	6.5 kHz tone (non-impulsive)	Harbour porpoise (1)
Kastelein et al. 2015a	Impact pile driving (impulsive)	Harbour porpoise (1)
Kastelein et al. 2015b	6-7 kHz sweeps (non-impulsive)	Harbour porpoise (1)
Finneran et al. 2015*	Single airgun producing shots (impulsive)*	Bottlenose dolphin (3)
Popov et al. 2015	Half-octave band noise (non-impulsive)	Beluga (1)
Kastelein et al. 2016*	Impact pile driving (impulsive)	Harbour porpoise (2)
Kastelein et al. 2017	Multiple air gun shots (SELcum 188/191 dB re 1 μPa2s)	Harbour porpoise (1 male, age 3)

+Peer reviewed studies available and evaluated as of 31 May 2016.

^Note: Some individuals have been used in multiple studies.

*No incidents of temporary threshold shift were recorded in study.

Information on hearing loss in marine mammals has been reviewed by Finneran (2015). One aspect of the NMFS (2016) exposure criteria that has been controversial is the use of weighting functions. The choice of weighting functions can have substantial implications for the assessment of noise exposure (Tougaard and Dähne 2017), and the NMFS (2016) approach may not always be appropriate (Tougaard et al. 2015). Exposure criteria are also generally based on received not source levels. It has been suggested that there is a need for the development of differing exposure criteria for multiple and single pulses of sound.

Anthropogenic sound interferences with hearing can cause marine mammals to interrupt their feeding, alter their vocalizations, or leave important habitat, among other behavioural and physiological responses. Data on sound-induced threshold shifts in marine mammals are available for only a few species and questions remain about extrapolating these results to other species.

A conceptual framework has been developed where the population consequences of disturbance to marine mammals can be linked to behavioural changes. This framework has centred around two approaches: i) a data-driven approach that uses bioenergetic models and a population dynamic model to identify disturbance scenarios that can potentially cause biologically significant or population-level responses (New et al. 2013, New et al. 2014, McHuron et al. 2017, Villegas-Amtmann et al. 2017, Farmer et al. 2018, Pirotta et al. 2018); and ii) an approach that uses the opinions of experts through an elicitation process combined with statistical analysis and a population dynamic model (Harwood et al. 2014, King et al. 2015, Fleishman et al. 2016).

Cetaceans

Cetaceans are the most studied aquatic mammals in regard to impacts due to exposure to anthropogenic noise. The state-of-knowledge of responses to sound exposures is fair to good and varies amongst cetacean species.

Behavioural responses

Different cetacean species exhibit differing behavioural responses when exposed to noise and generalizations are difficult to discern (Table 4; Senigaglia et al. 2016). The most recent review of the effects of naval sonar sounds on cetacean's behaviour is by Harris et al. (2017). A meta-analysis by Gomez et al. (2017) found received sound levels alone were not a good predictor of the magnitude of behavioural responses. Harris et al. (2017) found that functional hearing groups were not suitable for assessing the behavioural impacts of sonar, but the number of species studied was limited. A multi-species dose–response analysis showed that species could be grouped according to responsiveness or by predation risk and anti-predator strategies. Ellison et al. (2012) highlighted the importance of context in interpreting behavioural responses. Observed behavioural responses are energetically costly, however the consequences for long-term individual and population-level impacts is poorly understood (Harris et al. 2017).

Several publications recorded the responses of various whale species to sound exposure of various types and durations (Table 4). Falcone et al. (2017) observed reactions by Cuvier's beaked whales to military sonar signals with proximity of the signal being an important factor in response. Harris et al. (2017) showed that beaked whales exhibited the greatest response to naval sonar followed by sperm whales (*Physeter microcephalus*; Isojunno et al. 2016) and killer whales (*Orcinus orca*). Pilot whales (*Globicephala sp.*) appeared to be relatively tolerant of military sonar. Martin et al. (2015) observed a reduction in acoustic detection of minke whales in areas exposed to naval sounds. Kvadsheim et al. (2017) detected a five-fold increase in horizontal speed away from the source in tagged minke whales exposed to naval sonar. Sivle et al. (2016) found that naval sonar impacted humpback whales and that minke and bottlenose whales showed the most response. Results suggested that naval sonar exposure affected humpback whales' foraging behaviour in a way that might lead to negative fitness impacts. Dunlop et al.'s (2017) analysis of humpback whale behaviour responses to air gun sounds suggested that both proximity and received level were important factors in triggering avoidance behaviour.

Table 4. Examples of cetacean responses to anthropogenic sound (2012-2017).

Citation - location	Species	Sound Source	Methodology	Observations
Blair et al. 2016 – north Atlantic	Humpback whales	Ship noise	Archival tags – field observations	Effects on foraging, including slower descent rates and fewer side-roll feeding events per dive with increasing ship noise.
Cholewiak et al. 2017 – western North Atlantic	Beaked whales (4 species)	EK 60 (Scientific echosounder)	Towed hydrophone array deployed 300m behind the ship.	Interruption of foraging activity or vessel avoidance. A total of 183 beaked whale events were acoustically detected. Beaked whales were significantly less likely to be detected acoustically when echo-sounders were actively transmitting. A comparison of mean values from the best fit model for the BEAK dataset showed a 20-fold increase in detections when echo-sounders were in passive mode, regardless of region.
DeRuiter et al, 2013 – southern California	Beaked whales	Mid-frequency sonar	Tagged animals and playbacks	After ceasing normal fluking and echolocation, they swam rapidly, silently away, extending both dive duration and subsequent non-foraging interval. This is interpreted as a silent flight response, in which they moved away from the study area without echo-locating.
Dunlop 2016	Humpback whales	Vessel noise	In field observations (acoustic communication)	In increased vessel noise, there was no change in any measured vocal parameter.
Dunlop et al. 2017	Humpback Whale	air gun arrays (20 and 140 cubic inch)	Visual observations	Humpback whales were more likely to avoid the air gun arrays (but not the controls) within 3 km of the source at levels over 140 re 1μPa2 s−1.
Falcone et al. 2017 – southern California	Beaked whales	Mid-frequency active sonar	Satellite tags	Deep dives, shallow dives and surface intervals tended to become longer which contributed to longer intervals between deep dives, which again is considered a proxy for foraging disruption.
Finneran 2015 – southern California	Bottlenose dolphins	Seismic air gun (10 impulses)	Aquaria (?)	Behavioural reactions indicating that they were capable of anticipating and potentially mitigating the effects of impulsive sounds.
Isojunno et al. 2016 – location?	Killer whales	1-2 kHz sonar	Field data recorded by tags	Whales switched to a non-foraging, non-resting state. Time spent in foraging states and the probability of prey capture attempts were reduced.

Citation - location	**Species**	**Sound Source**	**Methodology**	**Observations**
Kvadsheim et al. 2017 – California and Norway	Minke whales	1-4 kHZ naval sonar	Tagged animals	Minke whales are likely to be affected by sonar across relatively large distances. Avoidance responses.
Lesage et al. 2017	Blue whales	Vessel noise	Measurement of changes in surface and diving patterns	Lost feeding opportunities due to avoidance responses.
Martin et al. 2015 - U.S. Navy's Pacific Missile Range Facility located off Kauai, Hawaii.	Minke Whale	MFAS Navy Sonar (1 – 10 kHz)	Bottom mounted hydrophones located in deep (>1 km) water -> automatic acoustic detection	
Pirotta et al. 2016 – Sydney, Australia	Humpback whales	Whale alarms	Field observations	Whales showed no detectable response to either alarm. Whale direction and surfacing behaviour did not differ whether the alarm was 'on' or 'off'.
Quick et al. 2016, Cape Hatteras, North Carolina	Short-finned whales	EK 60 Scientific echo sounder	Digital acoustic recording tags (DTAGs)	Regardless of behavioural state, the whales changed their heading more frequently when the echo sounder was active.
Sivle et al. 2015	Humpback whale, minke whale, Northern	Naval sonar (1-2 kHz)	Field observations of tagged animals	The most severe responses to sonar (severity 8) were progressive high-speed avoidance by the minke whale and long-term area avoidance by the bottlenose whale. Other severe responses included prolonged avoidance and cessation of feeding (severity 7). The minke whale and bottlenose whale started avoiding the source at a received sound pressure level (SPL) of 146 and 130 dB re 1 μPa, respectively.
Sivle et al. 2016	Humpback whales	Naval sonar	Field observations of tagged animals	Reduced foraging and negative impacts on energy balance.
Wensveen et al. 2017 –Barents Sea	Humpback whales	Sonar	Tagged whales approached with a ship to test sonar operation preceded by ramp-up	Sonar ramp-up has a positive but limited mitigative effect for humpback whales overall.

A response/no response dichotomous approach was recommended as a measure of impact in terms of habitat loss and degradation (Gomez et al. 2016).

Blair et al. (2016) found changes to humpback whale feeding behaviour in response to ship produced sounds and suggested that a reduction in foraging effort of individual whales might lead to population-level impacts. Blue whales reacted to mid-frequency (1-10 kHz) sonar signals (Goldbogen et al. 2013). Blue whales engaged in deep foraging were more likely to respond to the sonar than were whales feeding at shallower depths. Goldbogen et al. (2013) discussed energetic trade-offs as a possible explanation for their observations. Lesage et al. (2017) described reduced foraging by blue whales (*Balaenoptera musculus*) in response to vessel proximity (St Lawrence Estuary, Canada). Whale stranding is the most visible, and often controversial, behavioural response to anthropogenic noise (see pre-2012 literature). Naval sonar has been cited as the cause of the strandings of several species of whales, especially Cuvier's beaked whales (*Ziphius cavirostris*) (DeRuiter et al, 2013).

Analysis of stranding events and exposure experiments indicate that whale responses to anthropogenic sound are variable depending on the species, sound source characteristics and source-animal distance.

Signal Masking

It is known that anthropogenic noise from ship and/or seismic surveys can mask the detection of acoustic signals in cetaceans. In a review, Erbe et al. (2016) concluded that while the power-spectrum model of masking combined with critical ratios provide a simple and effective approach to predict the degree of masking, it does not account for several types of masking release (a decrease from expected masking mediated by a specific mechanism). They highly recommend studies on the effects of complex features and spatial segregation of signal and anthropogenic sound. Masking will also occur from natural sound sources, but Dunlop (2016) found different responses from humpback whales to wind and vessel-produced sound suggesting that whales may not be able to cope with anthropogenic sounds in the same way they cope with natural sounds.

Other Observations

Quick et al. (2016) reported a behavioural response of pilot whales (*Globicephala macrorhynchus*) to a Simrad EK60 scientific echo sounder (commonly used in Antarctica). Cholewiak et al. (2017) demonstrated a significant reduction in acoustic detections of beaked whales when an EK60 echo sounder was operating. A meta-analysis by Senigaglia et al. (2016) suggested that vessel proximity and the levels of sounds produced by whale-watching vessels influenced whale behavioural responses.

Acoustic harassment devices or ‘seal scarers’ use 12 kHz signals and have been shown to displace harbour porpoises (Mikkelsen et al. 2017). Sound signals from pingers and acoustic deterrent devices (ADDs) have been tested for the ability to displace marine mammals in order to prevent depredation, interactions with fishing gear or aquaculture, or to reduce the risk of injury from intense sound sources. Recent studies of 12 kHz signals from acoustic deterrents displaced harbour porpoises but less so harbour seals (*Phoca vitulina)* (Mikkelsen et al. 2017). In humpback whales, Pirotta et al. (2016) detected no responses to acoustic alarms emitting sound in the 2-5 kHz band designed to reduce entanglement risk.

Cetaceans are likely a priority for mitigation/management attention due to their iconic nature and the availability of research indicating the potential for impacts.

Pinnipeds

The state-of-knowledge of potential impacts of anthropogenic sound on pinnipeds is poor to fair. Much of the research on pinnipeds and sound has focused on effects on hearing (see the above section - Hearing Threshold Shifts in Marine Mammals).

Cunningham and Reichmuth (2016) found that pinnipeds can detect sounds at much higher frequencies than previous species hearing limits would suggest, including a response of a harbour seal to 140 kHz sound. Recent studies of responses of seals to pile-driving sounds associated with wind farm construction in the North Sea have shown displacement during the piling activity, starting from predicted received levels of between 166 and 178 dB re 1Pa (p-p), but no effect was observed within 2 hours of the cessation of pile driving (Russell et al. 2016). In a study of harbour seals around a windfarm construction site, Hastie et al. (2015) predicted that about half of the seals in the study would have been exposed to estimated permanent auditory damage thresholds. Jones et al. (2017) also found that both grey and harbour seals in UK waters had cumulative exposures greater than levels known to induce temporary threshold shift. These results suggest that pinnipeds may remain in an area even if they are exposed to sound levels that could cause injury. In addition to exposure injury, masking can be an issue for pinnipeds (Bagocius 2014). Sills (2017) evaluated how impulsive sound from seismic air guns can limit the detection of low-frequency sounds by ice-living seals and demonstrated that, even in complex masking scenarios, a simplistic model of masking can be sufficient to predict hearing loss under certain sound scenarios.

Fishes

The state-of-knowledge of potential impacts of anthropogenic sound on fishes is fair (Table 5).

Hearing, Physiological and Behavioural Response

Research into fish hearing has been limited, but there are likely key differences between species depending on their auditory anatomy (Hawkins and Popper 2017). Popper et al. (2014) broadly group fishes into those with and without swim bladders with the former being sensitive to only a narrow band of low frequencies and the latter only to particle motion. Fish with swim bladders linked to the ear, which are mainly sensitive to sound pressure, are also subject to particle motion and hearing can extend up to a few kHz. The fish groups found in Antarctic and sub-Antarctic waters (including skates and rays, *Myctophiformes*, *Gadiformes*, *Lampriformes*, *Liparidae*, *Perciformes* such as icefish, toothfish and *Notothenia*, *Pleuronectiformes*) include fishes with and without swim bladders, and therefore are dependent on a range of hearing mechanisms and sensitivities both in regard to particle motion and to sound pressure. In general, the signals used in experimental exposures have been mostly low frequency (e.g. ship produced sounds, seismic air guns, pile driving) and are expected to be within the estimated hearing range of the subject species. The majority of experiments have been laboratory, tank-based (aquaria) studies (Table 5).

Although there are differences in sensitivity to sound between fish taxa, responses to sound stimuli are sometimes different amongst individuals in a group (La Manna et al. 2016). Most experiments demonstrate behavioural and/or physiological responses to sound exposures, if only short-term. There are few data on physical effects of sound on fishes (Carroll et al. 2017). Radford et al. (2016) investigated potential chronic impacts by conducting longer-term (12 week) exposures. These laboratory-based exposure experiments with European seabass examined how the initial impact of different sound types changed over time. Fish exposed to impulsive sound showed elevated ventilation rates at the beginning of the experiment indicating heightened stress. However, fish exposed to playbacks of pile-driving or seismic sound for 12 weeks no longer showed these responses indicating an increased tolerance or a change in hearing threshold. These fishes showed no differences in stress, growth or mortality when comparing controls to those reared with exposure to ambient-sound playback though exposure times were limited. Cortisol concentrations were elevated at the start of the experiment and then declined after the first 30-60 minutes of exposure. Peña et al. (2013) did not observe responses in herring exposed to 3-D seismic air gun sound.

In several studies where behavioural changes were observed, investigators suggested that effects on fish might be greater or more chronic than immediately apparent. Some studies observed responses that may have implications for fish survival:

1) Reduced predator responses were observed in European eels that may impact fitness due to effects on life-death reactions (Simpson et al. 2015).
2) Minnows foraged less than those in control conditions and sticklebacks foraged at the same rate but made more mistakes possibly impacting fitness (Voellmy et al. 2014).
3) No behavioural reaction by *Gobius cruentatus* and *Chromis chromis* were observed on exposure to boat produced sound (Picciulin et al. 2010). However, a time-budget analysis revealed a significant change in the total time spent in caring for their nests (*C. chromis*) or inside their shelters (*G. cruentatus*).
4) Three-spined sticklebacks in a tank exposed to boat-sound-frequency recordings exhibited mild fear-related behaviours (Purser and Radford 2011). There was evidence that the addition of anthropogenic sound increased food-handling errors, reduced discrimination between food and non-food items, and decreased foraging efficiency, which may produce chronic impacts.
5) Low frequency sounds from shipping and other sources may mask communications between conspecific soniferous fish impacting reproductive success and survival through the incorrect assessment of the quality of potential mates or competitors and a decreased ability to attract mates (Radford et al. 2014; Stanley et al. 2017).

Experiments with several fish species have demonstrated behavioural responses to broadband impulsive pile driving sounds such as dispersal of sprat (*Sprattus sprattus)* schools and changes in depth by mackerel (*Scomber scombrus*) schools (Hawkins et al. 2014). Herbert-Read et al. (2017) observed that juvenile sea bass (*Dicentrarchus labrax*) exposed to playback of pile driving exhibited less cohesion and directional-ordering/coordination losing some of the benefits of group living. Neo et al. (2015) found that European sea bass changed their swim patterns (swimming faster and deeper) in response to impulsive sounds simulating pile driving or seismic air guns.

Population Level Responses

Table 5. Examples of fish responses to anthropogenic sound (2012-2017)

Citation	Species	Sound Source	Methodology	Observations
Bolle, et al. 2012	Sole larvae	Recorded pile driving sounds	Aquaria	No significant mortality
Bruinjtes et al. 2013	Co-operatively breeding fish	Playback of noise of a passing boat	Aquaria	Reduced digging behaviour, decreased defence against predators of eggs and fry and increased the amount of aggression received and submission shown by subordinates.
Hawkins et al. 2014	Pelagic fish	Sound playback of a sonar/ echo sounder	In a quiet coastal setting	Behavioural responses.
Herbert-Read et al. 2017	Sea bass	Pile driving sound playback	Aquaria	Affected the structure and dynamic of fish shoals.
La Manna et al. 2016	Brown meagre	Boat noise	In a field context	Behavioural responses.
Løkkeborg et al. 2012	Fishes	Seismic air gun	Field observations by acoustic mapping	Fish abundance did not suggest displacement from fishing grounds.
Neo et al. 2015	Seabass	Seismic shooting and pile driving	Outdoor basin	Changes in swimming patterns.
Paxton et al. 2017	Temperate reef fish	Seismic survey	Video recording of fish abundance and behaviour	Significant reduction in fish occupation of the reef
Peña et al. 2013	Herring	Seismic air gun surveys	Omnidirectional fisheries sonar	No changes were observed in swimming speed, swimming direction, or school size that could be attributed to the transmitting seismic vessel.
Radford et al. 2016	Sea bass	Impulsive sound	Aquaria	Indications of heightened stress.
Voellmy et al. 2014	Cod and haddock	Playback of ship noise	Field observations of tagged animals	Reduced food consumption.

There is no research on how sound affects fishes at the population level. However, a number of studies have documented impacts on essential activities of fishes that may have implications for population-level impacts including:

1) Short-term flight and hiding behaviour in response to boat sounds (brown meagre [*Sciaena umbra*], La Manna et al. 2016).

2) Reduction in the likelihood and speed of startle responses to predator ambush and pursuit when exposed to ship produced sound (juvenile European eels [*Anguilla Anguilla*] Simpson et al. 2015).
3) Less prey consumption and more startle responses to the playback of ship produced sound (three-spined sticklebacks [*Gasterosteus aculeatus*] and European minnows [*Phoxinus phoxinus*], (Voellmy et al. 2014).
4) Negative effects on nest digging and defence against predators when exposed to the playback of sounds from a passing boat (chichlid fish [*Neolamprologus pulcher*] (Bruintjes and Radford, 2013).
5) Movement to the bottom of the water column, faster swimming in more tightly cohesive groups and increases in alarm response in response to air gun sound (various marine species, Fewtrell and McCauley 2012).
6) Larvae of coral reef fish moved away from boat noise whereas they swam towards natural reef sounds in a sound-choice experiment suggesting that boat noise could affect larval settlement (Holles et al. 2013).

In field experiments observed that motorboat noise increased the susceptibility of Ambon damselfish (*Pomacentrus amboinensis*) to its natural predator the dusky dottyback (*Pseudochromis fuscus*) (Simpson et al. 2016). This study is one of the first to show that noise has a direct effect on demography implying population level consequences.

There have been concerns that anthropogenic sound, in particular seismic air gun sound, could affect catch rates for important fisheries (Carroll et al. 2017). Løkkeborg et al. (2012) found that there were changes in catch rates for all species of fishes they studied in relation to sounds from seismic air guns. Catch rates of species caught by longline, such as Greenland halibut (*Reinhardtius hippoglossoides*) and haddock fell in areas near seismic surveys. However, catches of species caught in gillnets doubled during the seismic survey shooting period as compared to pre-shooting. The increase in gillnet catches in response to air gun sound was attributed to behavioural responses to the sound such as increased activity and deeper swimming depths making the fish more vulnerable to gillnet capture. Lower longline catches may have been the result of sound reducing feeding activity, making the fish less likely to be caught on longlines. What is notable from this study is that fish behaviour was altered by sound regardless of whether the result was higher or lower catches.

Studies of fishes, while limited, have indicated possible hearing, physiological and behavioural responses to anthropogenic noise exposures. While there is no direct evidence, some of the observed responses may have implications for population/fisheries-level impacts. Differences in methodologies between experiments make comparisons difficult. There are no studies on the effects of anthropogenic sounds on Antarctic fishes. It is uncertain how, or if, the observed responses, or the lack of responses, in non-Antarctic fishes might be expressed in Antarctic fish species.

Invertebrates

The state-of-knowledge of potential impacts of anthropogenic sound on invertebrates is poor.

The statocyst is a sensory receptor that controls balance and position in marine invertebrates such as cephalopods, some bivalves, echinoderms and crustaceans. It is thought to be the primary means of sound perception (Carroll et al. 2017). In this regard it is the equivalent of a fish otolith. The statocyst, which develops during the larval phase, likely acts as an accelerometer in response to the vibratory particle motion component of sound (Samson et al. 2014). The particle motion component of a sound signal can propagate via the water column, the seabed, or both. Detection of substrate-borne low-frequency (<200Hz) vibration has been demonstrated to induce behavioural responses in some species of crustaceans and bivalves (Table 6; Roberts et al. 2015; Roberts and Elliott 2017). Although research in this area is limited, the high sensitivity of the invertebrates tested to substrate vibration across a broad range of frequencies has potential to impact at the individual, population and ecosystem levels through the disruption of behaviours (Solan et al. 2016). Many invertebrates are sessile or slow-moving having a limited capacity to avoid exposure to underwater sound (Edmonds et al. 2016).

Crustaceans

A review of the impacts of sound (both water-borne and substrate vibrations) on crustaceans demonstrated that they produce, detect and respond to sound (Edmonds et al. 2016).

Decapods

Tank and field studies have investigated behavioural and physiological responses in decapods on exposure to sound. The changes observed indicate stress responses with potential impacts on fitness due to starvation and/or predation. Observed behavioural impacts include changes in locomotor patterns, presence inside or outside a shelter, and changes to agonistic, foraging and anti-predator behaviours (Celi et al. 2013; Wale et al. 2013; Filiciotto et al. 2014; Filiciotto et al. 2016; Roberts and Elliott 2017). Physiological impacts include changes in protein concentrations in the haemolymph and brain, DNA integrity, the expression of protein levels in brain tissues and increases in oxygen consumption (Celi et al. 2013; Wale et al. 2013; Filiciotto et al. 2014; Filiciotto et al. 2016). Not all studies found sound exposure effects although studies were conducted over limited water depths and sample size was small. Some impacts are more difficult to detect and may only be expressed as long-term effects. Day et al. (2016) considered only the time period until hatching of Spiny lobster eggs (*Jasus edwardsii*) and concluded that embryonic spiny lobster are resilient to air gun signals. No difference in the quantity and quality of hatched larvae were detected. However, longer term effects were detected in lobsters exposed to seismic air guns signals. Stress responses and an immune response to pathogens were detected 120 and 365 days post-exposures raising concerns that air gun exposure might affect the immune system of lobsters (Fitzgibbon et al. 2017). Planktonic crustaceans, primarily Antarctic krill (*Euphausia superba*), are widespread in Antarctic marine environments. Exposure of zooplankton to seismic survey air guns resulted in a decrease in abundance and an increase in mortality of adult and larval zooplankton with impacts out to the maximum range sampled (1.2 km) including the death of all larval krill (*Nyctiphanes australis*) (McCauley et al. 2017).

Molluscs

Stress-related effects of sound on molluscs have been demonstrated such as disruption of natural valve periodicity in mussels (*Mytilus edulis*) and increases in recessing and flinch behaviours in scallops (*Pecten fumatus*: Roberts et al. 2015, Day et al. 2017) when exposed to low frequency sound. Day et al. (2017) exposed scallops (Pecten fumatus) to seismic air gun signals and found significantly increased mortality rates. Day et al. (2017) also noted both acute and chronic physiological effects in scallops in hemolymph biochemistry at a level considered to be harmful. Roberts et al. (2015) observed that the behavioural responses to sound, which are energetically expensive, are likely to impact the overall fitness of both individuals and mussel beds with possible ecosystem level implications.

Cephalopods

Several studies of cephalopods, both in tanks and in their natural habitat (primarily squid and cuttlefish species) indicate that they are behaviourally, anatomically and physiologically impacted by sound exposures. In some cases, these impacts are incompatible with survival. In addition to statocysts, cephalopods have epidermal hairs that detect close-range particle motion (Carroll et al. 2017). Behavioural responses included body-patterning changes and fin movements at all frequencies and levels of sound exposure, and alarm/defense/escape responses such as inking and jetting at lower frequencies and higher sound levels (Fewtrell and McCauley 2012, Solé et al. 2013(a); Samson et al. 2014; Mooney et al. 2016). This difference in sensitivity indicates a relative loudness concept in the cephalopods tested, and particular sensitivity to sounds below around 400 Hz. This overlaps with the main frequencies in both natural ambient ocean sound and anthropogenic sounds such as shipping and seismic air guns (Mooney et al. 2016). Behavioural and masking responses, which have unknown impacts at both individual and population levels are likely to be those most commonly experienced by cephalopods in response to loud, low frequency sound.

Table 6. Examples of invertebrate responses to anthropogenic sound (2012-2017).

Citation	Species	Sound Source	Methodology	Observations
Aguilar de Soto et al. 2013	Marine larvae	Playback of pre-recorded seismic air gun sounds	Aquaria	Noise exposure during larval development produces body malformations in marine invertebrates.
Celi, et al. 2013	Red swamp crayfish	Linear sweep (frequency range 0.1-25 kHz; peak amplitude 148 dB(rms) re. 1 μPa at 12 kHz) acoustic stimulus	Experiment was conducted in a tank equipped with a video recording system	Significant variations in haemato-immunological parameters as well as a reduction in agonistic behaviour.
Day et al. 2016	Spiny lobster eggs	Airgun	Pods in field based natural lobster habitat:	Hatched larvae were counted for fecundity, assessed for abnormal morphology using measurements of larval length and width, tested for larval competency using an established activity test and measured for energy content. Overall there were no differences in the quantity or quality of hatched larvae.
Day et al. 2017	Scallops	Sercel G Gun II operated at 2,000 psi. (at 45 + 150 cin)	Field-based experiments	Increased mortality rates; disrupted behavioural patterns and reflex response; and altered hemolymph biochemistry, physiology, and osmoregulation capacity.

Citation	Species	Sound Source	Methodology	Observations
Fewtrell and McCauley 2012	Squid	Air gun noise	Caged animal exposed in a bay setting	Fish respond by moving to the bottom of the water column and swimming faster in more tightly cohesive groups and an increase in the occurrence of alarm responses.
Filicotti et al. 2016	Common prawn	recorded boat noise	Aquaria	Physiological and behavioural responses to stress
Fitzgibbon et al. 2017	Spiny Lobster	Airgun noise	Controlled field experiments over shallow limestone reef platform	Suppression of total haemocyte count (THC) for up to 120 days post-exposure (indicator for stress response) and two-fold elevation of THC levels after 365 days post-exposure (indicator of an immune response to pathogens).
McCauley et al. 2017	Zoo-plankton	Single airgun (150 cin)	Field experiment: Density measurements by sonar and net tows	Zooplankton abundance decreased by ~3–4 dB within 15–30 min (sonar) and 64% decrease within 1 h (median in net tows) and caused a two- to three-fold increase in dead adult and larval zooplankton. Impacts were observed out to the maximum 1.2 km sample range.
Mooney et al. 2016	Long finned squid	Sounds from 80 to 1000 Hz	Tank experiments	Behavioural responses include fleeing, deimatic and protean behaviours.
Nedelec et al 2014	Sea Hare	Boat noise playback	Field experiment/ eggs with Eppendorff tubes	Boat-noise playback, compared to ambient-noise playback, reduced successful development of embryos by 21% and additionally increased mortality of recently hatched larvae by 22%.
Parry and Gason et al. 2017	Rock lobsters	Seismic surveys	In a field context	No evidence that catch rates of rock lobsters were affected.
Pine et al. 2012	Crabs	Turbine sound	Laboratory experiments	Interference with natural metamorphosis behaviour.
Przeslawski et al. 2018	Scallops	Seismic surveys	Field based studies	No adverse effects.
Solé et al. 2013 (a)	Cephalo-pod (4 species)	Underwater transducer generating 50–400 Hz sinusoidal wave sweeps	Controlled exposure experiment in tank	Lesions in the statocysts of all tested species and incremental effects over time, consistent with a massive acoustic trauma statocysts at received levels of (RL = 157±5 dB re 1 μPa (with peak levels up to SPL = 175 dB re 1 μPa).
Solé et al. 2013 (b)	Cephalo-pod	Controlled exposure experiments	Aquaria	Lesions and incremental effects over time, consistent with a massive acoustic trauma.

Citation	Species	Sound Source	Methodology	Observations
Solé et al. 2017	Cephalopod (Cuttlefish)	Underwater transducer generating 100–400 Hz sinusoidal wave sweeps	Offshore controlled exposure experiments measuring SP and PM	Injuries to statocyst at sound exposure levels of 139 to 142 dB re 1 µPa$^{2..}$
Wale et al. 2013 (a,b)	Crabs	Playback of ship noise	Controlled tank-based experiments	Higher oxygen consumption, indicating a higher metabolic rate and potentially greater stress.

However, anatomical damage resulting from sound exposure has also been recorded in cephalopods, mainly trauma to the statocyst and sensory hairs, affecting its functionality and physiology, which can be fatal (Solé et al. 2013(a); Solé et al. 2013(b); Solé et al. 2017).

Early Life Stages

Early life stages have been proposed as a potential bottleneck due to their presumed lower tolerance for various stressors however recent research suggests that there are fundamental differences in sensitivity of early life stages between species. Although this may not be as relevant to Antarctic invertebrates due to a low proportion of species having planktonic development, it remains an important consideration. Studies of larva mortality are important as the effects of sound need to take into account organisms' sensitivity and vulnerability to sound throughout their entire life history, including the larval stage (Edmonds et al. 2016). Results from studies on the effects of anthropogenic sound on larvae are varied. Malformations and developmental delays were found in scallop (*Pecten novaezelandiae*) larvae exposed to seismic pulses in aquaria (Aguilar de Soto et al. 2013). Delays in the metamorphosis of crab (*Austrohelice crassa* and *Hemigrapsus crenulatus*) larvae were observed on exposure to turbine sounds (Pine et al. 2012). However, Day et al. (2016) found that seismic pulses had no effect on spiny lobster (*Jasus edwardsii*) eggs. There was no increased mortality of common sole *(Solea solea*) larvae exposed to pile-driving sound, although this study only investigated mortality in the first seven days after exposure (Bolle et al. 2012).

Other Observations

Most research on invertebrates (and fishes) focuses on laboratory or caged animal experiments – translating these results to the field is difficult, and there is little knowledge about how an impact on a given species may translate to community or population level effects. Several authors suggest that energetically expensive behavioural responses are likely to impact individual fitness as well as populations. A review of the literature of the potential impacts of marine seismic surveys on invertebrates (and fishes) concluded: 1) generalizations about impacts are often inappropriate due to the gaps in knowledge about sound thresholds and recovery from impact and 2) a disparity exists between results obtained in the field and results from the laboratory (Carroll et al. 2017). As many invertebrates (and fishes) are sensitive to particle motion, rather than sound pressure, it is important to consider particle motion along with sound pressure when assessing impacts related to exposure to sound (Kunc et al. 2016).

While there is scientific evidence for high-intensity and low-frequency sound-induced physical trauma and other negative effects on some invertebrates, controversy remains about the methods used in and results from studies of responses in invertebrates to anthropogenic noise (Carrol et al 2017). Results from research on invertebrates in the laboratory are difficult to translate to real-world sound exposure scenarios. Understanding of the role that particle motion plays in sound exposure responses in invertebrates is limited but indications are that it may be important. There is little knowledge about how an impact on individual invertebrates translates to community or population-level effects. Understanding of how sound exposure effects early life stages of invertebrates is limited but there are some indications that it may be significant.

Seabirds

The state-of-knowledge of potential impacts of anthropogenic sound on seabirds is poor.

Land birds' use of sound and the impact of exposures to anthropogenic noise are well documented, however, the effects of underwater sound on diving seabirds are poorly described (Crowell et al. 2016). Many diving bird species use sound in air, with average audiograms following the U-shape typical of birds and many other animals; the bandwidth of greatest sensitivity tends to be from 1 to 3 kHz (Crowell et al. 2015; Thiebault et al. 2016; Hansen et al. 2017). However, few experiments have been carried out underwater. The middle ear of diving birds is adapted to protect against pressure changes suggesting that diving birds might not hear well underwater. However, the great cormorant's (*Phalacrocorax carbo*) hearing was better than expected with the greatest sensitivity at 2 kHz with an underwater hearing threshold of 71 dB re 1 µPa rms (comparable to those of bottlenose dolphins, harbour porpoises, and true seals in the 1 to 4 kHz frequency band; Hansen et al. 2017) and an in-air hearing threshold of 18 dB re 20 µPa rms (Maxwell et al. 2017). Hansen et al. (2017) speculated that aquatic birds that perform long or deep dives, like penguins, might be adapted to use sound underwater. Pichegru et al. (2017) demonstrated that African penguins showed an avoidance of preferred foraging areas reaction during seismic activities.

There is little data on the effect of underwater sounds on Antarctic diving birds including iconic penguin species.

Sound Sensitive Antarctic species and sound "hotspots"

Scientific evidence to identify which Antarctic species may be most vulnerable to anthropogenic sound exposure is incomplete, however early research results do point to candidate species.

Cetaceans

Baleen whales have a high-energy demand which is estimated to be around 3-4 % of their body weight per day. Therefore, loss of feeding opportunities because of hearing impairment or disturbance could have impacts. Lunge feeding of blue whales is a rather costly energetic foraging strategy that relies on large patches of prey (Goldbogen et al. 2013a). Lesage et al. (2017) describe a significant reduction in foraging time related to vessel proximity and Goldbogen et al (2013b) demonstrate sonar-induced disruption of feeding and displacement from high-quality prey patches which could impact blue whale foraging ecology. These observations suggest that interference by anthropogenic noise may impact individual fitness and, in the case of endangered species like the blue whale, have population consequences which, depending on the outcomes of further studies, could qualify lunge feeders as "sound sensitive".

Mid-frequency beaked whales are rarely sighted animals in all oceans due to their inconspicuous behaviour. Therefore, a lack of sightings in the Southern Ocean does not necessarily indicate a lack of presence. Beaked whales, as a deep-diving family, require access to foraging habitat. Reviewing the collective account of Arnoux Beakes Whale sightings and considering the numerous intrusions of deep-water channels and canyons on the western side of the Antarctic Peninsula, the nearshore waters on the western side of the Antarctic Peninsula provide suitable habitat for Arnoux's beaked whales. Beaked whales have shown avoidance reaction at considerably lower sound levels than other cetacean species (e.g. DeRuiter et al. 2013) and have been involved in the majority of stranding events related to naval sonar and therefore, depending on the outcomes of further studies based on exposure to sound sources found in Antarctica, could be considered "sound sensitive".

Some cetacean species are a likely high priority group for protection due to their iconic status and the availability of research indicating potential impacts.

Invertebrates

Invertebrates like cephalopods or zooplankton species like krill or copepods play a vital role in the Antarctic food web. Studies indicate that these organisms might be more sensible to underwater anthropogenic noise than other species (Sole et al. 2017 and McCauley et al. 2017). Sole et al. (2017) tested animals in natural offshore environments and demonstrated that cephalopods experience injuries in their statocysts after being exposed to sound levels ranging from 139 to 142 dB re 1 μPa2 and from 139 to 141 dB re 1 μPa^2, at 1/3 octave bands centred at 315 Hz and 400 Hz, respectively. They suggest that these results could be considered a coherent threshold estimation of sound levels for acoustic trauma in cephalopods. McCauley et al. (2017) demonstrated an increase in the mortality rate for zooplankton from a natural level of 19 % per day to 45 % per day after ensonification with air gun signals up to a distance of 1.2 km. Considering the important role of cephalopods and zooplankton in the Antarctic food web, the described effects could qualify these organism groups as "sound sensitive" depending on the outcomes of further studies. As indicated above, much remains unknown in regard to the effects of sound on invertebrates, differential effects on life stages and the methods utilized to study effects remain controversial (Caroll et al. 2017).

"Sound hotspots"

Related to a consideration of sound sensitive species, or species targeted for conservation for other reasons, is their juxtaposition with the geographic and temporal locations of anthropogenic sound sources (Gomez et al. 2017). Given the gaps in knowledge identified in this report, confidence in identifying sound "hot spots", locations that might be most likely to experience sound at levels of concern, is low. However, the location of intense sound sources or higher levels of anthropogenic sound may be discernable. Critical habitat for marine life that might be vulnerable to sound would also need to be identified. Suitable habitats and areas with higher abundances of organisms could be one proxy for critical habitats. Additionally, areas identified in plans for marine protected areas, Antarctic Specially Protected Areas and Antarctic Specially Managed Areas might be a starting point (e.g. Espinasse et al. 2012, Santora 2013, Santora & Veit 2013, Bouchet et al. 2015, Ballard et al. 2012, Ainley et al. 2017).

Predicting High Risk Scenarios

To illustrate how predicting the intersection of high-risk noise exposure areas and sound sensitive species might be used to prioritize where mitigation and/or management practice would be most needed and/or effective, the Antarctic Peninsula is considered. As a first step, ship density for the area could be evaluated including tourist, fishing, research and operator vessels and the locations of scientific stations utilizing geospatial data (Bender et al. 2016; e.g., IAATO scheduler, COMNAP notifications and CCAMLR Vessel Mapping System). While modelling sound might be useful, the complex topography of the peninsular region makes it difficult to predict sound levels at specific locations and times. To predict the risk from anthropogenic noise it would be best to monitor *in situ* anthropogenic sound levels. Vulnerable species distributions along the peninsula would then need to be considered and whether the sound levels predicted and/or observed would be expected to impact individuals, populations and/or access to critical habitats. Temporal patterns in species distributions must be considered as some Antarctic species have short mating periods or noise sensitive foraging behaviour patterns. For some species, sound plays an important role in mate finding and selection and masking during limited periods of time might have an impact on the breeding success. The Antarctic summer is of vital importance for the yearly energy balance of several species. Foraging as a sequence of complex behaviour patterns has been shown to be sensitive to acoustic disturbance in some species. Within the region there are also a number of Antarctic Specially Protected Areas, Antarctic Specially Managed Areas and the US has a Long Term Ecological Research site in the waters of the Western Antarctic Peninsula that could provide critical background information on targets for protection. The Specially Protected Species Ross Seal are also known to inhabit the region. This region is subject to cumulative effects (see below) given the warming climate in the region and the associated glacier retreat, changing sea ice conditions, predicted ocean acidification and observed changes in biota distributions.

Identification of areas of concentrated anthropogenic noise (sound “hotspots”) and species judged to be sensitive to sound exposure (“sound sensitive species”) would inform policy by providing an indication of the juxtaposition of areas of greatest risk of exposure with distributions of the most vulnerable species allowing for prioritization and targeting of mitigation/management efforts to greatest effect.

Cumulative Impacts

There has been progress in regard to the general issue of evaluating cumulative impacts, however this remains a complex issue (National Research Council 2017). Wright & Kyhn (2015) provided a practical approach for marine examples and Williams et al. (2016) show for two whale populations an approach to define cumulative, sub-lethal effects. In the context of the Antarctic Treaty, cumulative impacts would not only address the question of cumulative impacts from noise sources but also other environmental stressors (decline of ice, ocean acidification, increased temperatures etc.). To illustrate the complexity in regard to sound alone, multiple noise sources might include a ship with several echo sounders/sonars, concurrent sounds from different emitters, and/or a sequence of sound sources passing a specific location that result in extended periods of increased noise levels.

Cumulative effects of anthropogenic sound on animal populations may result from repeated interruptions of feeding, displacement from breading areas, elevated levels of stress hormones, masking of communications, masking of predator sounds and extension of migration tracks. These effects may be particularly detrimental to small, endangered populations.

Mitigation and Management

The state-of-knowledge regarding the effectiveness of mitigation and management approaches to anthropogenic sound in the oceans is poor to fair with few studies that quantify the success of mitigation and/or management efforts.

Mitigation strategies for reducing impacts of anthropogenic sound involve either limiting the source level or propagation of the sound, or separating the sound source from the species of concern. Studies of the effectiveness of operational mitigation (km range around source) conclude that the effectiveness of some mitigation efforts is unclear. Strategic mitigation (i.e. aiming for a spatial segregation at 100’s of km) requires detailed knowledge of the temporal and spatial distributions and movements of populations, which is available for only a few species in Antarctica.

Modification of Sound Generating Operations

For sources such as seismic or sonar, operational mitigation to date has largely focused on limiting impacts on marine mammals. Reducing the power of the source or shutting it down if vulnerable species are close is commonly used in an attempt to reduce the risk of injury.

Ramping up of sources in the hope that animals move away before being exposed to a noise level that would cause injury is a common practice (reviewed in Nowacek et al. 2013). Recent evidence casts doubt on the effectiveness of ramping up as a mitigation strategy for humpback whales (Dunlop et al 2016, Wensveen et al. 2017). Von Benda-Beckmann et al. (2014) emphasize the need for careful empirical tests of whether the ramp up procedure used is well designed to reduce the risk of impacts. Further they argue that ramp-up beyond five minutes has limited effectiveness and induces excess avoidance responses in scenarios for naval sonar. Wensveen et al. (2017) found that most humpback whales did not exhibit strong avoidance responses to sonar signals. The findings of Dunlop et al. (2016) in relation to migrating humpback whales exposed to air gun ramp-up were similar. However, they also point out that ramp-up can reduce the risk of harm more effectively in situations when animals are more responsive and likely to avoid the sound source (e.g. owing to novelty of the stimulus) when they are in the path of an approaching sonar ship. Forney et al. (2017) showed that attempting to minimize injury by enabling animals to move away is inadequate or even counterproductive for small, localized marine mammal populations, for which displacement of animals may cause harm. Air guns have been designed to reduce high frequency energy that may impact animals such as odontocetes that hear best at high frequencies though seismic surveys can and do expose animals to measurable levels of higher frequency energy.

Principles and guidelines for seismic surveys are described by Nowacek et al. (2013). EIAs for seismic surveys south of 60° S typically include descriptions of the geophysical characteristics of the applied sound sources, the sound propagation and the mitigation radii (Breitzke 2014). Lynch et al. (2016) expressed concern, that recently revised guidelines for EIA of the ATCM (Resolution 1 (2016) - Revised Guidelines for Environmental Impact Assessment in Antarctica) do not explicitly request quantitative information on wildlife abundance.

In addition to local operation measures, global initiatives to reduce shipping sounds at the source through ship quieting technologies may reduce the impact of vessels. Prins et al. (2016) describe a set of guidelines for regulators which discuss the definitions, numerical and experimental methods and mitigation solutions for underwater sound radiated from ships.

Operational mitigation strategies for scientific sonars and echo-sounders include switching off transmissions unless needed for safety of navigation or scientific data collection. Switching to only transmitting the highest frequency transducer suitable for the situation may reduce the potential for impacts. This needs to be counterbalanced by the increased hearing sensitivity of some species at higher frequency.

Marine Mammal Observers, Passive Acoustic Monitoring and Infrared Thermography

The most commonly-used marine mammal sound mitigation regime includes Marine Mammal Observers (MMO) or Passive Acoustic Monitoring (PAM) to detect animals close to the source during ramp up or to instigate a shut down during normal operations (Leaper et al. 2015).

The effectiveness of shut downs using MMOs has rarely been quantified. Leaper et al.'s (2015) simulation model showed that the use of MMOs resulted in minimal reduction in exposure risk. The study also indicated that small reductions in source level will generally be a more effective way of reducing injury risk than shut downs in response to cetacean sightings. The probability of Marine Observers detecting marine mammals depends on good visibility and having the animals surface and produce a visible cue. The probability of detecting many marine mammals is below 100% along the track-line and this probability decreases with range. Most surveys in Antarctica are rarely conducted at night but can be conducted in conditions of poor visibility when visual observations are largely ineffective. Methods for monitoring marine mammals in low visibility conditions were recently reviewed by Verfuss et al. (2018). Zitterbart et al. (2013) have developed an Infrared System and tested it in the Antarctic to automatically detect whales to assist MMO in their decision-making.

In some instances, seismic surveys have been shown to disrupt behaviour and cause avoidance responses in marine mammal species beyond the ranges of detection by receivers or observers on board the source ship. Remedies to this uncertainty might include conducting an animal survey before the seismic survey. If the abundance of mammal species in an area raises concerns about impact, monitoring strategies with a demonstrated ability to detect a high enough proportion of animals within the impact zone for effective mitigation are preferred. In 2015, Italy introduced a mandatory monitoring protocol for offshore seismic activities to compare marine mammal presence before, during and after seismic surveys (Fossati et al. 2017). Recent technological developments (e.g., buoys, gliders, drones) may be effective alternative observing platforms to the source vessel. As with any mitigation efforts, cost may be a limiting factor.

Verfuss et al. (2018) point out that no single monitoring method is likely to be able to detect all animals in all conditions and environments. They recommend the use of a combination of two or more methods to improve detection probability for real-time monitoring and to improve in-time detection.

Avoidance of High Densities of Biota

Understanding the distribution of sensitive species and avoiding high-density areas can be an effective mitigation measure for activities that do not need to be carried out in a specific location or time. In some areas, seasonal high densities can be avoided by adjusting the timing of sound-producing activities, but this is likely to be difficult in the Antarctic due to the short summer season and remoteness. Emphasis on early season seismic surveys has been effective in minimizing exposure of gray whales to seismic noise in northern waters (Muir et al. 2016). Bombosch et al. (2014) suggested that predictive modelling may provide ways to manage the location and timing of seismic surveys to minimize impacts on Antarctic cetacean species. However, this approach requires adequate data to model species distribution that are often lacking or are difficult to obtain for most species. Gomez et al. (2017) followed a slightly different approach developing their species distribution model which can be iterative, adapted by including updated data as it becomes available to further refine and validate the modelling results. Proposed mitigation activities should assess the uncertainty in model predictions for species distribution patterns.

Changes in shipping routes can limit sound exposure in sensitive areas. Predictable localized distribution patterns at the scale of shipping routes may be easier to model than the larger areas affected by seismic surveys. Such changes in routes have been implemented in a number of areas to address ship strikes and are recognized by IMO as an effective way to address that issue but could also be used to reduce noise exposure. The IMO Polar Code specifically requires marine mammal distributions to be taken into account in voyage planning.

There is a lack of rigorous evidence-based assessments of mitigation and management protocols used elsewhere in the world's ocean in a context of quantifiable accomplishment of explicit conservation/protection goals. There are no such studies specifically in the Antarctic region or for Antarctic species. No single monitoring method is likely to be able to detect all animals in all conditions and environments, therefore a combination of methods will improve the effectiveness of real-time monitoring and the probability of in-time detection (Verfuss et al. 2018).

Concluding Remarks

Compared to other regions of the world's oceans, Antarctic marine environments experience low levels of anthropogenic noise, although natural ambient sound levels can be high because of the presence and interactions of ice in various forms. Knowledge of the interactions of Antarctic species, populations and ecosystems with anthropogenic noise in the marine environment remains limited. What understanding does exist is often difficult to reliably extrapolate to real-world scenarios due to an incomplete understanding of the response of receptor species and moderating environmental factors. If progress in policy formulation regarding anthropogenic noise is to be made, directed research that explores a range of environments, taxa and sound sources specific to Antarctic marine environments is required. Research outcomes from elsewhere in the world's oceans and in the laboratory may provide useful guidance for Antarctic environments but must be used with caution. Given the mixed results from studies investigating the impact of sound exposures on different species, sexes and life-history stages, caution must be taken when extrapolating results between species and amongst life stages.

There remain significant gaps in scientific knowledge on a range of important issues essential to advancing evidence-based policy-making regarding the impacts of noise in Antarctic marine environments (within the references cited there are topic specific recommendations for research and study not repeated here). Addressing critical gaps in knowledge will require:

1. **Expanding the scope of studies of species and taxonomic groups' exposure-response to anthropogenic noise with particular reference to Antarctic species (including transients)**. Understanding and management frameworks for addressing the impacts of underwater sound on marine mammals are more advanced than for other taxa. Further exploration of behavioural responses to anthropogenic noise exposures including masking is needed. In recent years there has been some research on fish and invertebrates while experimental methods remain controversial. A refined understanding of fishes and invertebrate responses to anthropogenic noise exposure and the role of particle motion is needed. The utilization of sound and the impact of anthropogenic noise on diving-birds remains poorly understood. Expanding research to include ontogenic variation (i.e. differences between life stages) is needed as sound may differentially affect embryos, larvae, juveniles and adults. Better defining the population and ecosystem-level consequences of anthropogenic sound exposures is required. Assessing possible long-term and cumulative effects of anthropogenic noise on individuals and populations including chronic, multi-source sound and multi-stressor impacts should be investigated. Further studies are needed to prioritize Antarctic species for protection based on scientific evidence of sensitivity to real-world scenarios of sound exposures in Antarctic marine environments.
2. **Standardizing methodologies, experimental approaches and metrics of effectiveness to improve cross-comparisons of results.** There has been some improvement in consistency in experimental and monitoring methodologies facilitating cross-study comparisons but wide variations in practice persist. Further standardization will ensure that diverse studies of the impacts of sound exposure are comparable and that real-world exposure scenarios can be formulated. A clear set of standards for monitoring sound in the marine environment (including terminology, appropriate calibrations for low-frequency sound measurements and agreed methods and units for the measurement for impulsive, chronic, and cumulative sound) is needed. Recent progress in this area includes International Organization of Standards (ISO) 18405:2017 which defines terms and expressions used in the field of underwater acoustics, including natural, biological and anthropogenic (i.e., man-made) sound.
3. **Addressing the lack of knowledge of spatial and temporal variations in ambient sound in Antarctica** as the basis for evaluating real-world scenarios of anthropogenic noise exposure. Mapping of sound around Antarctica remains challenging. Understanding more about natural sound and its variability is important for predicting potential impacts due to additions of anthropogenic sound which together determine ambient sound exposures.
4. **Improving knowledge of the spatial and temporal scales of anthropogenic sound sources, characteristics, distributions (spatial and temporal) and levels in Antarctic waters**. An evaluation of sound from all ships and sound sources on ships (scientific, tourism and fishing vessels) is needed. Detailed mapping of the various sound sources, timing, acoustic properties and sound

intensity will better define realistic Antarctic sound scenarios. Validation of sound modelling in Antarctic environments with monitoring of realistic potential sound sources is needed. There is an increasing number of acoustic recorders being deployed in Antarctic marine waters which in time will allow more robust development of models and validation of predictions. Sound modelling in Antarctic environments needs to be validated with data from *in situ* monitoring of sound. Better knowledge of the soundscape will clarify when sound becomes noise.

5. **Conducting risk assessments that determine the likelihood that individuals and populations will be exposed to harmful levels of sound.** Monitoring of sound would produce realistic geospatially defined estimates of the potential for noise exposures. In other regions of the world's ocean acoustic arrays of hydrophones have been deployed. These sensors record ambient sound as well as specific sources of sound. To properly assess the risk of detrimental noise exposures to marine wildlife, a distributed system in Antarctica should focus on locations of human activity such as Antarctic bases, shipping lanes, tourist sites and areas where there is limited or no human activity as controls. There are several ongoing efforts within SCAR that are developing better species distribution maps that would inform about the potential for exposure (e.g., the SCAR Expert Group on Birds and Marine Mammals has synthesized available tracking data for a range of seabirds and marine mammals, SCAR-MarBIN (Marine Biodiversity Information Network) has developed predictive habitat maps for a wide range of Antarctic organisms that predict where species are located). It is also important to consider the intersection of anthropogenic noise generating activities with other protection measures already in place such as Antarctic Specially Protected Species, Antarctic Specially Protected Areas, Antarctic Specially Managed Areas and Marine Protected Areas.
6. **Facilitating accessibility to all types of data and encouraging data sharing across all issues**. Bringing together existing data on ship transits, ship sound profiles (e.g., sound levels, sound spectrums etc.) and the timing, frequency and duration of ship voyages is needed. It is important to assess the abundance and quality of other sounds sources (such as seismic and bathymetric surveys) as well as the use of under ice Argo floats and the acoustic transmissions of Sound Fixing and Ranging [SOFAR] floats. Other important data includes animal distributions (see [5] above), environmental data required to predict sound transmission and propagation modelling and data on effects.
7. **Improving mitigation and management solutions** through engineering modifications to reduce sound at the source, identifying source spectra that minimize adverse impacts while meeting goals of use, testing the effectiveness of operational modifications and improving methods to predict the spatio-temporal distribution patterns of vulnerable species such that sensitive areas might be avoided. Promote rigorous evidence-based assessment of mitigation and management protocols.
8. **Continuing to monitor developments in regard to anthropogenic sound in the Southern Ocean** to detect significant changes in the state-of-knowledge on a wide range of important topics on an ongoing basis. Annually there are 1-2 conferences on the issue of sound and marine life and tens or more journal publications reflecting the complexity and scope of the issues involved.
9. **Fostering a collaborative relationship between regulators, scientists, industry and policymakers** to identify practical and implementable best practices for mitigating and managing anthropogenic sound in the Southern Ocean within a framework of optimizing costs and benefits.

Anthropogenic noise in the world’s ocean will continue to be of wide interest for the foreseeable future as oceanic sound levels continue to increase and concerns about impacts on wildlife are clarified. Formulation of robust mitigation and management actions will require a more complete understanding of a diverse set of factors including, but not limited to, ambient sound levels and the unique characteristics of Antarctic species and marine environments that moderate noise exposures. Better definition of the vulnerabilities of species and life stages, and when anthropogenic sounds become noise, will be essential for effective mitigation and management strategies. A better understanding of how organisms, populations and ecosystems respond to anthropogenic noise in the context of complex and multiple environmental pressures, including a changing and warming climate, will be critical.

References

Aguilar de Soto, N., N. Delorme, J. Atkins, S. Howard, J. Williams and M. Johnson (2013). Anthropogenic noise causes body malformations and delays development in marine larvae. Science Report 3: 2831.

Ainley, D. G., Lindke, K., Ballard, G., Lyver, P. O. B., Jennings, S., Toniolo, V., . . . Santora, J. A. (2017). Spatio-temporal occurrence patterns of cetaceans near Ross Island, Antarctica, 2002–2015: implications for food web dynamics. Polar Biology 40(9): 1761-1775.

Bagocius, D. (2014). Potential masking of the Baltic grey seal vocalisations by underwater shipping noise in the Lithuanian area of the Baltic Sea. Environmental Research, Engineering and Management 4: 66-72.

Bender, N. A., Crosbie, K. and Lynch, H. J. (2016). Patterns of tourism in the Antarctic Peninsula region: a 20-year analysis. Antarctic Science: 1-10.

Blair, H. B., N. D. Merchant, A. S. Friedlaender, D. N. Wiley and S. E. Parks (2016). Evidence for ship noise impacts on humpback whale foraging behaviour. Biol Lett 12(8).

Bolle, L. J., C. A. F. de Jong, S. M. Bierman, P. J. G. van Beek, O. A. van Keeken, P. W. Wessels, C. J. G. van Damme, H. V. Winter, D. de Haan and R. P. A. Dekeling (2012). Common Sole Larvae Survive High Levels of Pile-Driving Sound in Controlled Exposure Experiments. PLOS ONE 7(3): e33052.

Bombosch, A., D. P. Zitterbart, I. van Opzeeland, S. Frickenhaus, E. Burkhardt, M. S. Wisz and O. Boebel (2014). Predictive habitat modelling of humpback (*Megaptera novaeangliae*) and Antarctic minke (*Balaenoptera bonaerensis*) whales in the Southern Ocean as a planning tool for seismic surveys. Deep Sea Research Part I: Oceanographic Research Papers 91: 101-114.

Breitzke, M. (2014). Overview of seismic research activities in the Southern Ocean - quantifying the environmental impact. Antarctic Science 26(1): 80-92.

Breitzke, M. and T. Bohlen (2010). Modelling sound propagation in the Southern Ocean to estimate the acoustic impact of seismic research surveys on marine mammals. Geophysical Journal International 181: 818-846.

Bruintjes, R. and A. N. Radford (2013). Context-dependent impacts of anthropogenic noise on individual and social behaviour in a cooperatively breeding fish. Animal Behaviour 85(6): 1343-1349.

Carroll, A. G., R. Przeslawski, A. Duncan, M. Gunning and B. Bruce (2017). A critical review of the potential impacts of marine seismic surveys on fish & invertebrates. Marine Pollution Bulletin 114: 9-24.

Celi, M., F. Filiciotto, D. Parrinello, G. Buscaino, M. A. Damiano, A. Cuttitta, S. D'Angelo, S. Mazzola and M. Vazzana (2013). Physiological and agonistic behavioural response of Procambarus clarkii to an acoustic stimulus. J Exp Biol 216(Pt 4): 709-718.

Cholewiak, D., DeAngelis, A. I., Palka, D., Corkeron, P. J. and Van Parijs, S. M. (2017). Beaked whales demonstrate a marked acoustic response to the use of shipboard echosounders. Royal Society Open Science 4(12): 170940.

Crowell, S. E., A. M. Wells-Berlin, C. E. Carr, G. H. Olsen, R. E. Therrien, S. E. Yannuzzi and D. R. Ketten (2015). A comparison of auditory brainstem responses across diving bird species. Journal of Comparative Physiology A 201(8): 803-815.

Crowell, S. E., Wells-Berlin, A. M., Therrien, R. E., Yannuzzi, S. E. and Carr, C. E. (2016). In-air hearing of a diving duck: A comparison of psychoacoustic and auditory brainstem response thresholds. The Journal of the Acoustical Society of America 139(5): 3001.

Day, R D., R.D. McCauley, Q.P. Fitzgibbon, K. Hartmann and J.M. Semmens. (2017). Exposure to seismic air gun signals causes physiological harm and alters behavior in the scallop Pecten fumatus. PNAS. 114: E8537–E8546.

Day, R. D., R. D. McCauley, Q. P. Fitzgibbon and J. M. Semmens (2016). Seismic air gun exposure during early-stage embryonic development does not negatively affect spiny lobster *Jasus edwardsii* larvae (Decapoda:Palinuridae). Scientific Reports 6: 22723.

DeRuiter, S. L., B. L. Southall, J. Calambokidis, W. M. X. Zimmer, D. Sadykova, E. A. Falcone, A. S. Friedlaender, J. E. Joseph, D. Moretti, G. S. Schorr, L. Thomas and P. L. Tyack (2013). First direct measurements of behavioural responses by Cuvier's beaked whales to mid-frequency active sonar. Biol. Lett. 9(4): 20130223.

Dunlop, R. A. (2016). The effect of vessel noise on humpback whale, *Megaptera novaeangliae,* communication behaviour. Animal Behaviour 111(Supplement C): 13-21.

Dunlop, R. A., M. J. Noad, R. D. McCauley, E. Kniest, R. Slade, D. Paton and D. H. Cato (2016). Response of humpback whales (*Megaptera novaeangliae*) to ramp-up of a small experimental air gun array. Marine Pollution Bulletin 103: 72-83.

Dunlop, R. A., M. J. Noad, R. D. McCauley, L. Scott-Hayward, E. Kniest, R. Slade, D. Paton and D. H. Cato (2017). Determining the behavioural dose-response relationship of marine mammals to air gun noise and source proximity. J Exp Biol 220(Pt 16): 2878-2886.

Dziak, R. P., D. R. Bohnenstiehl, K. M. Stafford, H. Matsumoto, M. Park, W. S. Lee, M. J. Fowler, T.-K. Lau, J. H. Haxel and D. K. Mellinger (2015). Sources and Levels of Ambient Ocean Sound near the Antarctic Peninsula. PLOS ONE 10(4): e0123425.

Edmonds, N. J., C. J. Firmin, D. Goldsmith, R. C. Faulkner and D. T. Wood (2016). A review of crustacean sensitivity to high amplitude underwater noise: Data needs for effective risk assessment in relation to UK commercial species. Marine Pollution Bulletin 108: 5-11.

Ellison, W. T., B. L. Southall, C. W. Clark and A. S. Frankel (2012). A New Context-Based Approach to Assess Marine Mammal Behavioral Responses to Anthropogenic Sounds. Conservation Biology 26: 21–28.

Erbe, C., C. Reichmuth, K. Cunningham, K. Lucke and R. Dooling (2016). Communication masking in marine mammals: A review and research strategy. Marine Pollution Bulletin 103(1): 15-38.

Espinasse, B., Zhou, M., Zhu, Y., Hazen, E. L., Friedlaender, A. S., Nowacek, D. P., . . . Carlotti, F. (2012). Austral fall-winter transition of mesozooplankton assemblages and krill aggregations in an embayment west of the Antarctic Peninsula. Marine Ecology Progress Series 452: 63-80.

Falcone, E. A., Schorr, G. S., Watwood, S. L., DeRuiter, S. L., Zerbini, A. N., Andrews, R. D., . . . Moretti, D. J. (2017). Diving behaviour of Cuvier's beaked whales exposed to two types of military sonar. Royal Society Open Science 4(8): 170629.

Farmer, N. A., D. P. Noren, E. M. Fougères, A. Machernis, and K. Baker. 2018. Resilience of the endangered sperm whale Physeter macrocephalus to foraging disturbance in the Gulf of Mexico, USA: a bioenergetic approach. Marine Ecology Progress Series 589:241-261.

Fewtrell, J. L. and R. D. McCauley (2012). Impact of air gun noise on the behaviour of marine fish and squid. Marine Pollution Bulletin 64: 984-993.

Filiciotto, F., M. Vazzana, M. Celi, V. Maccarrone, M. Ceraulo, G. Buffa, V. Arizza, G. de Vincenzi, R. Grammauta, S. Mazzola and G. Buscaino (2016). Underwater noise from boats: Measurement of its influence on the behaviour and biochemistry of the common prawn (*Palaemon serratus,* Pennant 1777). Journal of Experimental Marine Biology and Ecology 478(Supplement C): 24-33.

Filiciotto, F., M. Vazzana, M. Celi, V. Maccarrone, M. Ceraulo, G. Buffa, V. D. Stefano, S. Mazzola and G. Buscaino (2014). Behavioural and biochemical stress responses of *Palinurus elephas* after exposure to boat noise pollution in tank. Marine Pollution Bulletin 84: 104-114.

Finneran, J. J. (2015). Noise-induced hearing loss in marine mammals: A review of temporary threshold shift studies from 1996 to 2015. The Journal of the Acoustical Society of America 138: 1702-1726.

Finneran, J. J., C. E. Schlundt, B. K. Branstetter, J. S. Trickey, V. Bowman, and K. Jenkins. 2015. Effects of multiple impulses from a seismic air gun on bottlenose dolphin hearing and behavior. Journal of the Acoustical Society of America 137:1634-1646.

Finneran, J.J. and Schlundt, C.E. (2013). Effects of fatiguing tone frequency on temporary threshold shift in bottlenose dolphins (*Tursiops truncatus*). Journal of the Acoustical Society of America 133: 1819-1826.

Finneran, J.J., Schlundt, C.E., Branstetter, B.K., Trickey, J., Bowman, V., and Jenkins, K. (2015). Effects of multiple impulses from a seismic air gun on bottlenose dolphin hearing and behavior, Journal of the Acoustical Society of America 137: 1634-1646.

Fitzgibbon, Q. P., Day, R. D., McCauley, R. D., Simon, C. J. and Semmens, J. M. (2017). The impact of seismic air gun exposure on the haemolymph physiology and nutritional condition of spiny lobster, Jasus edwardsii. Marine Pollution Bulletin 125: 146-156.

Fleishman, E., D. P. Costa, J. Harwood, S. Kraus, D. Moretti, L. F. New, R. S. Schick, L. K. Schwarz, S. E. Simmons, L. Thomas, and R. S. Wells. 2016. Monitoring population-level responses of marine mammals to human activities. Marine Mammal Science 32:1004-1021.

Forney, K. A., B. L. Southall, E. Slooten, S. Dawson, A. J. Read, R. W. Baird and R. L. Brownell, Jr. (2017). Nowhere to go: noise impact assessments for marine mammal populations with high site fidelity. Endangered Species Research 32: 391-413.

Fossati, C., Mussi, B., Tizzi, R., Pavan, G. and Pace, D. S. (2017). Italy introduces pre and post operation monitoring phases for offshore seismic exploration activities. Marine Pollution Bulletin 120:376-378.

Goldbogen, J. A., Calambokidis, J., Friedlaender, A. S., Francis, J., DeRuiter, S. L., Stimpert, A. K., . . . Southall, B. L. (2013b). Underwater acrobatics by the world's largest predator: 360 degrees rolling manoeuvres by lunge-feeding blue whales. Biol Lett 9(1): 20120986.

Goldbogen, J.A., B.L. Southall, S.L. DeRuiter…..2013a. Blue whales respond to simulated mid-frequency military sonar. Proceddings of the Royal Society B. 280:20130657.

Gomez, C., Lawson, J., Kouwenberg, A. L., Moors-Murphy, H., Buren, A., Fuentes-Yaco, C.,… Wimmer, T. (2017). Predicted distribution of whales at risk: identifying priority areas to enhance cetacean monitoring in the Northwest Atlantic Ocean. Endangered Species Research 32: 437-458.

Hansen, K. A., A. Maxwell, U. Siebert, O. N. Larsen and M. Wahlberg (2017). Great cormorants (*Phalacrocorax carbo*) can detect auditory cues while diving. The Science of Nature 104(5): 45.

Harris, C. M., L. Thomas, E. A. Falcone, J. Hildebrand, D. Houser, P. H. Kvadsheim, F.-P. A. Lam, P. J. O. Miller, D. J. Moretti, A. J. Read, H. Slabbekoorn, B. L. Southall, P. L. Tyack, D. Wartzok and V. M. Janik (2017). Marine mammals and sonar: dose-response studies, the risk-disturbance hypothesis and the role of exposure context." Journal of Applied Ecology 55: 396–404.

Harwood, J., S. King, R. Schick, C. Donovan, and C. Booth. 2014. A protocol for implementing the interim population consequences of disturbance (PCoD) approach: Quantifying and assessing the effects of UK offshore renewable energy developments on marine mammal populations: Report number SMRUL-TCE-2013-014. Scott Mar Freshwater Sci 5:2.

Hastie, G. D., D. J. F. Russell, B. McConnell, S. Moss, D. Thompson and V. M. Janik (2015). Sound exposure in harbour seals during the installation of an offshore wind farm: predictions of auditory damage. Journal of Applied Ecology 52: 631-640.

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

Hawkins, A. D., L. Roberts and S. Cheesman (2014). Responses of free-living coastal pelagic fish to impulsive sounds. Journal of the Acoustical Society of America 135(5): 3101-3116.

Herbert-Read, J. E., L. Kremer, R. Bruintjes, A. N. Radford and C. C. Ioannou (2017). Anthropogenic noise pollution from pile-driving disrupts the structure and dynamics of fish shoals. Proc Biol Sci 284(1863).

Holles, S., S. D. Simpson, A. N. Radford, L. Berten, and D. Lecchini. 2013. Boat noise disrupts orientation behaviour in a coral reef fish. Marine Ecology Progress Series 485:295-300.

Isojunno, S., C. Cure, P. H. Kvadsheim, F. P. Lam, P. L. Tyack, P. J. Wensveen and P. J. Miller (2016). Sperm whales reduce foraging effort during exposure to 1-2 kHz sonar and killer whale sounds. Ecol Appl 26(1): 77-93.

Jakobsson, M., R. Gyllencreutz, L. A. Mayer, J. A. Dowdeswell, M. Canals, B. J. Todd, E. K. Dowdeswell, K. A. Hogan and R. D. Larter (2016). Mapping submarine glacial landforms using acoustic methods. Geological Society, London, Memoirs 46(1): 17.

Jones, E. L., G. D. Hastie, S. Smout, J. Onoufriou, N. D. Merchant, K. L. Brookes and D. Thompson (2017). Seals and shipping. Journal of Applied Ecology 54, 1930–1940.

Kastelein, R.A., Gransier, R., and Hoek, L. (2013a). Comparative temporary threshold shifts in a harbor porpoise and harbor seal, and severe shift in a seal. Journal of the Acoustical Society of America 134, 13-16.

Kastelein, R.A., Gransier, R., Hoek, L., and Olthuis, J. (2012a). Temporary threshold shifts and recovery in a harbor porpoise (*Phocoena phocoena*) after octave-band noise at 4 kHz. Journal of the Acoustical Society of America 132, 3525-3537.

Kastelein, R.A., Gransier, R., Hoek, L., and Rambags, M. (2013b). Hearing frequency thresholds of a harbor porpoise (*Phocoena phocoena*) temporarily affected by a continuous 1.5 kHz tone. Journal of the Acoustical Society of America 134, 2286-2292.

Kastelein, R.A., Gransier, R., Hoek, L., Macleod, A., and Terhune, J.M. (2012b). Hearing threshold shifts and recovery in harbor seals (*Phoca vitulina*) after octave-band noise exposure at 4 kHz, Journal of the Acoustical Society of America 132, 2745-2761.

Kastelein, R.A., Gransier, R., Schop, J., and Hoek, L. (2015b). Effects of exposure to intermittent and continuous 6–7 kHz sonar sweeps on harbor porpoise (*Phocoena phocoena*) hearing, Journal of the Acoustical Society of America 137, 1623-1633.

Kastelein, R.A., L. Helder-Hoek, J. Covi, and R. Gransier. 2016. Pile driving playback sound and temporary threshold shift in harbor porpoises (*Phocoena phocoena*): Effect of exposure duration. Journal of the Acoustical Society of America 139:2842-2851.

Kastelein, R.A., Schop, J., Gransier, R., and Hoek, L. (2014a). Frequency of greatest temporary hearing threshold shift in harbor porpoises (*Phocoena phocoena)* depends on the noise level. Journal of the Acoustical Society of America 136, 1410-1418.

Kastelein, R.A., Hoek, L., Gransier, R., Rambags, M., and Claeys, N. (2014b). Effect of level, duration, and inter-pulse interval of 1-2 kHz sonar signal exposures on harbor porpoise hearing, The Journal of the Acoustical Society of America 136, 412-422.

Kastelein, R.A., Schop, J., Hoek, L., and Covi, J. (2015a). Hearing thresholds of a harbor porpoise (*Phocoena phocoena*) for narrow-band sweeps, The Journal of the Acoustical Society of America 138, 2508-2512.

King, S. L., R. S. Schick, C. Donovan, C. G. Booth, M. Burgman, L. Thomas and J. Harwood (2015). An interim framework for assessing the population consequences of disturbance. Methods in Ecology and Evolution 6: 1150-1158.

Kunc, H., K. McLaughlin and R. Schmidt (2016). Aquatic noise pollution: implications for individuals, populations, and ecosystems. Proceedings. Biological sciences, The Royal Society 283(1836).

Kvadsheim, P. H., S. DeRuiter, L. D. Sivle, J. Goldbogen, R. Roland-Hansen, P. J. O. Miller, F.-P. A. Lam, J. Calambokidis, A. Friedlaender, F. Visser, P. L. Tyack, L. Kleivane and B. Southall (2017). Avoidance responses of minke whales to 1–4kHz naval sonar. Marine Pollution Bulletin 121(1): 60-68.

La Manna, G., M. Manghi, F. Perretti and G. Sarà (2016). Behavioral response of brown meagre (*Sciaena umbra*) to boat noise. Marine Pollution Bulletin 110(1): 324-334.

Leaper, R., S. Calderan and J. Cooke (2015). A Simulation Framework to Evaluate the Efficiency of Using Visual Observers to Reduce the Risk of Injury from Loud Sound Sources. Aquatic Mammals 41: 375-387.

Lesage, V., A. Omrane, T. Doniol-Valcroze and A. Mosnier (2017). Increased proximity of vessels reduces feeding opportunities of blue whales in the St. Lawrence Estuary, Canada. Endangered Species Research 32: 351-361.

Løkkeborg, S., E. Ona, A. Vold and A. Salthaug (2012). Sounds from seismic air guns: gear- and species-specific effects on catch rates and fish distribution. Canadian Journal of Fisheries and Aquatic Sciences 69(8): 1278-1291.

Lynch, M. A., Foley, C. M., Thorne, L. H. and Lynch, H. J. (2016). Improving the use of biological data in Antarctic management. Antarctic Science 28(06): 425-431.

Martin, S., C.R. Martin, B.M. Matsuyama, and E.E. Henderson. (2015). Minke whales (*Balaenoptera acutorostrata*) respond to navy training. J Acoust. Soc. Am. 137(5): 2533-2541."

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

Maxwell, A., Hansen, K. A., Ortiz, S. T., Larsen, O. N., Siebert, U. and Wahlberg, M. (2017). In-air hearing of the great cormorant (*Phalacrocorax carbo*). Biol Open 6(4): 496-502.

McCauley, R. D., R. D. Day, K. M. Swadling, Q. P. Fitzgibbon, R. A. Watson and J. M. Semmens (2017). Widely used marine seismic survey air gun operations negatively impact zooplankton. Nature Ecology & Evolution 1: Article 0195.

McHuron, E. A., D. P. Costa, L. Schwarz, and M. Mangel. 2017. State-dependent behavioural theory for assessing the fitness consequences of anthropogenic disturbance on capital and income breeders. Methods in Ecology and Evolution 8:552-560.

Menze, S., D. P. Zitterbart, I. van Opzeeland and O. Boebel (2017). The influence of sea ice, wind speed and marine mammals on Southern Ocean ambient sound. Royal Society Open Science 4(1).

New, L. F., D. J. Moretti, S. K. Hooker, D. P. Costa and S. E. Simmons (2013). Using Energetic Models to Investigate the Survival and Reproduction of Beaked Whales (family Ziphiidae). PLoS ONE 8(7): e68725.

New, L. F., J. S. Clark, D. P. Costa, E. Fleishman, M. A. Hindell, T. Klanjšček, D. Lusseau, S. Kraus, C. R. McMahon, P. W. Robinson, R. S. Schick, L. K. Schwarz, S. E. Simmons, L. Thomas, P. Tyack and J. Harwood (2014). Using short-term measures of behaviour to estimate long-term fitness of southern elephant seals. Marine Ecology Progress Series 496: 99-108.

Mikkelsen, L., L. Hermannsen, K. Beedholm, P. T. Madsen and J. Tougaard (2017). Simulated seal scarer sounds scare porpoises, but not seals: species-specific responses to 12 kHz deterrence sounds. Royal Society Open Science 4(7).

Miksis-Olds, J. L. and S. M. Nichols (2016). Is low frequency ocean sound increasing globally? The Journal of the Acoustical Society of America 139(1): 501-511.

Mooney, T. A., J. E. Samson, A. D. Schlunk and S. Zacarias (2016). Loudness-dependent behavioral responses and habituation to sound by the longfin squid (*Doryteuthis pealeii*). J Comp Physiol A Neuroethol Sens Neural Behav Physiol 202(7): 489-501.

Muir, J. E., Ainsworth, L., Racca, R., Bychkov, Y., Gailey, G., Vladimirov, V. ... & Bröker, K. (2016). Gray whale densities during a seismic survey off Sakhalin Island, Russia. Endangered Species Research, 29(3), 211-227.

National Marine Fisheries Service. 2016. Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts. U.S. Dept. of Commerce, NOAA. NOAA Technical Memorandum NMFS-OPR-55, 178 p.

National Research Council. 2017. Approaches to Understanding the Cumulative Effects of Stressors on Marine Mammals. The National Academies Press, Washington, DC.146 p.

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

Nedelec, S. L., Radford, A. N., Simpson, S. D., Nedelec, B., Lecchini, D. and Mills, S. C. (2014). Anthropogenic noise playback impairs embryonic development and increases mortality in a marine invertebrate. Scientific Reports 4: 5891.

Neo, E., E. Ufkes, R. Kastelein, H. V Winter, C. Ten Cate and H. Slabbekoorn (2015). Impulsive sounds change European seabass swimming patterns: Influence of pulse repetition interval. Marine Pollution Bulletin 97: 111-117.

Nowacek, D. P., C. W. Clark, D. Mann, P. J. O. Miller, H. C. Rosenbaum, J. S. Golden, M. Jasny, J. Kraska and B. L. Southall (2015). Marine seismic surveys and ocean noise: time for coordinated and prudent planning. Frontiers in Ecology and the Environment 13(7): 378-386.

Nowacek, D. P., K. Bröker, G. Donovan, G. Gailey, R. Racca, R. R. Reeves, A. I. Vedenev, D. W. Weller and B. L. Southall (2013). Responsible practices for minimizing and monitoring environmental impacts of marine seismic surveys with an emphasis on marine mammals. Aquatic Mammals 39(4): 356-377.

Paxton, A. B., Taylor, J. C., Nowacek, D. P., Dale, J., Cole, E., Voss, C. M., & Peterson, C. H. (2017). Seismic survey noise disrupted fish use of a temperate reef. Marine Policy, 78, 68-73.

Peña, H., N. O. Handegard and E. Ona (2013). Feeding herring schools do not react to seismic air gun surveys. ICES Journal of Marine Science 70(6): 1174-1180.

Picciulin, M., L. Sebastianutto, A. Codarin, A. Farina and E. A. Ferrero (2010). *In situ* behavioural responses to boat noise exposure of *Gobius cruentatus* (Gmelin, 1789; fam. Gobiidae) and *Chromis chromis* (Linnaeus, 1758; fam. Pomacentridae) living in a Marine Protected Area. Journal of Experimental Marine Biology and Ecology 386(1): 125-132.

Pichegru, L., Nyengera, R., McInnes, A. M. and Pistorius, P. (2017). Avoidance of seismic survey activities by penguins. Scientific reports 7(1): 16305.

Pine, M. K., A. G. Jeffs and C. A. Radford (2012). Turbine sound may influence the metamorphosis behaviour of estuarine crab *Megalopae*. PLOS ONE 7(12): e51790.

Pirotta, V., D. Slip, I. D. Jonsen, V. M. Peddemors, D. H. Cato, G. Ross and R. Harcourt (2016). Migrating humpback whales show no detectable response to whale alarms off Sydney, Australia. Endangered Species Research 29(3): 201-209.

Pirotta, E., M. Mangel, D. P. Costa, B. Mate, J. A. Goldbogen, D. M. Palacios, L. A. Huckstadt, E. A. McHuron, L. Schwarz, and L. New. 2018. A Dynamic State Model of Migratory Behavior and Physiology to Assess the Consequences of Environmental Variation and Anthropogenic Disturbance on Marine Vertebrates. Am Nat 191: E40-E56.

Popov, V.V., Nechaev, D.I., Sysueva, E.V., Rozhnov, V.V., and Supin, A.Y. (2015). Spectrum pattern resolution after noise exposure in a beluga whale, *Delphinapterus leucas*: Evoked potential study, J. Acoust. Soc. Am. 138, 377- 388.

Popov, V.V., Supin, A.Y., Rozhnov, V.V., Nechaev, D.I., Sysuyeva, E.V., Klishin, V.O., Pletenko, M.G., and Tarakanov, M.B. (2013). Hearing threshold shifts and recovery after noise exposure in beluga whales *Delphinapterus leucas*. J. Exp. Biol. 216, 1587-1596.

Prins, H. J., M. B. Flikkema, J. Bosschers, Y. Koldenhof, C. A. F. de Jong, C. Pestelli, H. Mumm, H. Bretschneider, V. Humphrey and M. Hyensjö (2016). Suppression of Underwater Noise Induced by Cavitation: SONIC. Transportation Research Procedia 14 (Supplement C): 2668-2677.

Przeslawski et al (2018) Multiple field-based methods to assess the potential impacts of seismic surveys on scallops. Mar Poll Bull. https://doi.org/10.1016/j.marpolbul.2017.10.066

Purser, J. and A. N. Radford (2011). "Acoustic Noise Induces Attention Shifts and Reduces Foraging Performance in Three-Spined Sticklebacks (*Gasterosteus aculeatus*). PLOS ONE 6(2): e17478.

Quick, N., L. Scott-Hayward, D. Sadykova, D. Nowacek and A. Read (2016). Effects of a scientific echo sounder on the behavior of short-finned pilot whales (*Globicephala macrorhynchus*). Canadian Journal of Fisheries and Aquatic Sciences 74(5): 716-726.

Radford, A. N., E. Kerridge and S. D. Simpson (2014). Acoustic communication in a noisy world: can fish compete with anthropogenic noise? Behavioral Ecology 25(5): 1022-1030.

Radford, A. N., Lebre, L., Lecaillon, G., Nedelec, S. L. and Simpson, S. D. (2016). Repeated exposure reduces the response to impulsive noise in European seabass. Global Change Biology 22(10): 3349-3360.

Reichmuth, C., A. Ghoul, J. M. Sills, A. Rouse, and B. L. Southall. 2016. Low-frequency temporary threshold shift not observed in spotted or ringed seals exposed to single air gun impulses. The Journal of the Acoustical Society of America 140:2646-2658.

Roberts, L. and M. Elliott (2017). Good or bad vibrations? Impacts of anthropogenic vibration on the marine epibenthos.Science of The Total Environment 595: 255-268

Roberts, L., S. Cheesman, M. Elliott and T. Breithaupt (2016). Sensitivity of *Pagurus bernhardus* (L.) to substrate-borne vibration and anthropogenic noise.Journal of Experimental Marine Biology and Ecology 474 (2016) 185–194.

Roberts, L., S. Cheesman, T. Breithaupt and M. Elliott (2015). Sensitivity of the mussel *Mytilus edulis* to substrate-borne vibration in relation to anthropogenically-generated noise. Marine Ecology Progress Series Volume: 538 Pages: 185-195

Roth, E. H., V. Schmidt, J. A. Hildebrand and S. M. Wiggins (2013). Underwater radiated noise levels of a research icebreaker in the central Arctic Ocean. The Journal of the Acoustical Society of America 133(4).

Russell, D. J. F., G. D. Hastie, D. Thompson, V. M. Janik, P. S. Hammond, L. A. S. Scott-Hayward, J. Matthiopoulos, E. L. Jones and B. J. McConnell (2016). Avoidance of wind farms by harbour seals is limited to pile driving activities. Journal of Applied Ecology 53(6): 1642-1652.

Samson, J. E., T. A. Mooney, S. W. S. Gussekloo and R. T. Hanlon (2014). Graded behavioral responses and habituation to sound in the common cuttlefish, *Sepia officinalis*. The Journal of Experimental Biology 217:4.

Santora, J. A. (2013). Dynamic intra-seasonal habitat use by Antarctic fur seals suggests migratory hotspots near the Antarctic Peninsula. Marine biology 160(6): 1383-1393.

Santora, J. A. and Veit, R. R. (2013). Spatio-temporal persistence of top predator hotspots near the Antarctic Peninsula. Marine Ecology Progress Series 487: 287-304.

Senigaglia, V., F. Christiansen, L. Bejder, D. Gendron, D. Lundquist, D. P. Noren, A. Schaffar, J. C. Smith, R. Williams, E. Martinez, K. Stockin and D. Lusseau (2016). Meta-analyses of whale-watching impact studies: comparisons of cetacean responses to disturbance. Marine Ecology Progress Series 542: 251-263.

Simpson, S. D., J. Purser and A. N. Radford (2015). Anthropogenic noise compromises antipredator behaviour in European eels. Global Change Biology 21(2): 586-593.

Simpson, S. D., A. N. Radford, S. L. Nedelec, M. C. Ferrari, D. P. Chivers, M. I. McCormick, and M. G. Meekan (2016). Anthropogenic noise increases fish mortality by predation. Nature communications 7:10544.

Sivle, L. D., P. J. Wensveen, P. H. Kvadsheim, F. P. A. Lam, F. Visser, C. Curé, C. M. Harris, P. L. Tyack and P. J. O. Miller (2016). Naval sonar disrupts foraging in humpback whales. Marine Ecology Progress Series 562: 211-220.

Solan, M., C. Hauton, J. A. Godbold, C. L. Wood, T. G. Leighton and P. White (2016). Anthropogenic sources of underwater sound can modify how sediment-dwelling invertebrates mediate ecosystem properties. Scientific Reports 6: 20540.

Solé, M., M. Lenoir, M. Durfort, M. López-Bejar, A. Lombarte and M. André (2013(a)). Ultrastructural Damage of *Loligo vulgaris* and *Illex coindetii* statocysts after Low Frequency Sound Exposure. PLOS ONE 8(10): e78825.

Solé, M., M. Lenoir, M. Durfort, M. López-Bejar, A. Lombarte, M. van der Schaar and M. André (2013(b)). Does exposure to noise from human activities compromise sensory information from cephalopod statocysts? Deep Sea Research Part II: Topical Studies in Oceanography 95(Supplement C): 160-181.

Solé, M., Sigray, P., Lenoir, M., van der Schaar, M., Lalander, E. and Andre, M. (2017). Offshore exposure experiments on cuttlefish indicate received sound pressure and particle motion levels associated with acoustic trauma. Scientific Reports 7: 45899.

Stanley, J. A., S. M. Van Parijs and L. T. Hatch (2017). Underwater sound from vessel traffic reduces the effective communication range in Atlantic cod and haddock. Scientific Reports 7(1): 14633.

Thiebault, A., P. Pistorius, R. Mullers and Y. Tremblay (2016). Seabird acoustic communication at sea: a new perspective using bio-logging devices. Scientific Reports 6: 30972.

Tougaard, J. and M. Dähne (2017). Why is auditory frequency weighting so important in regulation of underwater noise? The Journal of the Acoustical Society of America 142(4): EL415-EL420.

Tougaard, J., A. J. Wright and P. T. Madsen (2015). Cetacean noise criteria revisited in the light of proposed exposure limits for harbour porpoises. Marine Pollution Bulletin 90(1): 196-208.

Verfuss U.K., D. Gillespie, J. Gordon, T. A. Marques, B. Miller, R. Plunkett, J. A. Theriault, D. J. Tollit, D. P. Zitterbart, P. Hubert, and L. Thomas (2018). Comparing methods suitable for monitoring marine mammals in low visibility conditions during seismic surveys. Marine pollution bulletin 126: 1-18.

Villegas-Amtmann, S., L. K. Schwarz, G. Gailey, O. Sychenko, and D. P. Costa. 2017. East or west: the energetic cost of being a gray whale and the consequence of losing energy to disturbance. Endangered Species Research 34:167-183.

Voellmy, I., J. Purser, D. Flynn, P. Kennedy, S. Simpson and A. Radford (2014). Acoustic noise reduces foraging success in two sympatric fish species via different mechanisms. Animal Behaviour, 89, pp.191-198.

von Benda□Beckmann, A.M., Wensveen, P.J., Kvadsheim, P.H., LAM, F.P.A., Miller, P.J., Tyack, P.L. and Ainslie, M.A. (2014). Modeling effectiveness of gradual increases in source level to mitigate effects of sonar on marine mammals. Conservation biology, 28(1), pp.119-128.

Wale, M. A., S. D. Simpson and A. N. Radford (2013a). Noise negatively affects foraging and antipredator behaviour in shore crabs. Animal Behaviour 86(1): 111-118.

Wale, M. A., S. D. Simpson and A. N. Radford (2013b). Size-dependent physiological responses of shore crabs to single and repeated playback of ship noise. Biology Letters 9(2).

Wensveen Paul J. , Petter H. Kvadsheim, Frans-Peter A. Lam, Alexander M. von Benda-Beckmann, Lise D. Sivle, Fleur Visser, Charlotte Curé, Peter L. Tyack, Patrick J. O. Miller. (2017) Lack of behavioural responses of humpback whales (*Megaptera novaeangliae)* indicate limited effectiveness of sonar mitigation. Journal of Experimental Biology 2017 220: 4150-4161.

Williams, R., Thomas, L., Ashe, E., Clark, C. W. and Hammond, P. S. (2016). Gauging allowable harm limits to cumulative, sub-lethal effects of human activities on wildlife: A case-study approach using two whale populations. Marine Policy 70: 58-64.

Wright, A. J. and Kyhn, L. A. (2015). Practical management of cumulative anthropogenic impacts with working marine examples. Conservation Biology 29(2): 333-340.

Zitterbart DP, Kindermann L, Burkhardt E, Boebel O (2013) Automatic Round-the-Clock Detection of Whales for Mitigation from Underwater Noise Impacts. PLOS ONE 8(8): e71217. https://doi.org/10.1371/journal.pone.0071217

Appendix: List of acronyms

ATCM	Antarctic Treaty Consultative Meeting
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources
CEP	Committee for Environmental Protection (Antarctic Treaty)
COMNAP	Council of Managers of National Antarctic Programs
dB	decibel
DTAG	digital acoustic recording tag
EIA	Environmental impact assessment
FM	frequency modulation
IAATO	International Association of Antarctica Tour Operators
IMO	International Maritime Organization
IP	Information Paper
kHz	kiloHertz
MarBIN	Marine Biodiversity Information Network
MFAS	multifunction active sensor
MMO	Marine Mammal Observers
NMFS	National Marine Fisheries Service
Pa	Pascal (unit of pressure)
PAM	Passive Acoustic Monitoring
PTS	Permanent Threshold Shift
RL	received level (of noise)
ROV	Remotely Operated (underwater) Vehicle
SCAR	Scientific Committee on Antarctic Research
SOFAR	Sound Fixing and Ranging
SPL	Sound Pressure Level
TTS	Temporary Threshold Shift
UAV	Unmanned Aerial Vehicle
US / USA	United States of America
WP	Working Paper