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Final report

Detrimental effects of underwater noise

Development of the basics for a noise protection concept for Antarctica

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Abstract: Detrimental effects of underwater noise – Development of the basics for a noise protection concept for Antarctica

All activities in the Antarctic, which are organised in Germany or proceed from its territory, require an official permit from the German Environment Agency (UBA) as the national competent authority designated by the Act Implementing the Protocol on Environmental Protection to the Antarctic Treaty (AIEP). The Protocol on Environmental Protection to the Antarctic Treaty (EP) protects native animals at a population level and native mammals and birds at the individual level, prohibiting activities that molest, handle, capture, injure or kill a native mammal or bird (Annex II, EP).

Anthropogenic noise can molest, injure or even lead to death of marine mammals. Therefore, applications to carry out activities in the Antarctic that lead to the emission of underwater noise are often categorised to have at least a minor or temporary impact on marine mammal species or their populations. As a result, UBA need to conduct an Initial Environmental Evaluation (IEE) of applications based on an Initial Environmental Study (IES) provided by the applicant. As many as twenty-six marine mammal species inhabit the waters south of 60°S. Two panels of experts were invited to participate in an Expert Elicitation (EE) process, with varying backgrounds in behavioural response studies or auditory injury for a range of marine mammal species. Pre-workshop webinars were hosted with the invited experts, and short studies were provided to the experts to assist with summarising the information on the noise sources, Antarctic marine mammal species abundances and distributions, and a review of the current state of knowledge of behavioural responses of marine mammals to anthropogenic noise.

This project has developed new thresholds to support improved impact assessments for molest and injury following exposure to specific noise stressors. A detailed impact assessment approach is outlined, that could be a target for implementation for future environmental impact assessments (noting some elements are already considered). We also provide an evaluation approach that could be used to help set a numerical threshold of the number of animals impacted by an activity. We identify key evidence gaps and provide recommendations to further improve this process.

Kurzbeschreibung: Schädigende Wirkung von Unterwasserschall – Entwicklung der Grundlagen für ein Schallschutzkonzept Antarktis

Alle Tätigkeiten in der Antarktis, die in Deutschland organisiert werden oder vom deutschen Hoheitsgebiet ausgehen, bedürfen einer Genehmigung des Umweltbundesamtes (UBA) als nationaler zuständiger Behörde, die durch das Gesetz zur Ausführung des Umweltschutzprotokolls zum Antarktis-Vertrag (AUG) benannt wurde. Das Umweltschutzprotokoll zum Antarktis-Vertrag (USP) schützt einheimische Tiere auf Populationsebene und einheimische Säugetiere und Vögel auf Individuenebene, indem es verbietet, einheimische Säugetiere oder Vögel zu stören, zu berühren, zu fangen, zu verletzen oder zu töten (Annex II, USP).

Vom Menschen verursachter Lärm kann Meeressäuger erheblich stören, verletzen oder sogar zu deren Tod führen. Daher werden Tätigkeiten in der Antarktis, die Unterwasserlärm erzeugen, oft als Tätigkeiten eingestuft, die zumindest geringfügige oder vorübergehende Auswirkungen auf Arten von Meeressäugern oder deren Populationen haben. Deshalb muss das UBA eine Umwelterheblichkeitsprüfung der Anträge auf der Grundlage einer Umwelterheblichkeitsstudie durchführen, die vom Antragstellenden vorzulegen ist. Bis zu sechsundzwanzig Meeressäugerarten kommen in den Gewässern südlich von 60°S vor. Zwei Expertengruppen mit unterschiedlichem Hintergrund in der Erforschung von Verhaltensreaktionen oder Hörschäden bei einer Reihe von Meeressäugerspezies wurden zur Teilnahme an einem Expert-Elicitation-Prozess (EE) eingeladen. Vor den Workshops wurden Webinare mit den eingeladenen Experten und Expertinnen durchgeführt und ihnen Kurzstudien zur Verfügung gestellt, die Informationen über die Lärmquellen, die Abundanz und die Verteilung der antarktischen Meeressäugerarten zusammenfassen sowie einen Überblick über den derzeitigen Wissensstand über die Verhaltensreaktionen von Meeressäugern auf anthropogenen Lärm geben.

Im Rahmen dieses Projekts wurden neue Grenzwerte entwickelt, um eine bessere Folgenabschätzung für Störungen und Verletzungen von Meeressäugern infolge der Belastung durch bestimmte Lärmstressoren zu ermöglichen. Es wird ein detaillierter Ansatz zur Folgenabschätzung skizziert, der als Ziel für die Umsetzung zukünftiger Umweltprüfungen dienen könnte (wobei einige Elemente bereits berücksichtigt werden). Wir stellen auch einen Bewertungsansatz vor, der zur Festlegung eines numerischen Grenzwerts für die Anzahl der von einer Tätigkeit betroffenen Tiere verwendet werden könnte. Wir weisen auf wichtige Beweislücken hin und geben Empfehlungen zur weiteren Verbesserung dieses Prozesses.

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List of abbreviations

Abbreviation	Explanation
ACC	Antarctic Circumpolar Current
AEP	Auditory Evoked Potential
AIEP	Act Implementing the EP
AIMMMS	Automated Infrared-based Marine Mammal Mitigation System
APF	Antarctic Polar Front
ASSO	Atlantic sector of the Southern Ocean
ASV	Autonomous Surface Vehicles
AUV	Autonomous Underwater Vehicles
AWI	Alfred Wegener Institute for Polar and Marine Research
BMUV	Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection
CEE	Controlled Exposure Experiment
CF	Continuous Frequency
CMS	Convention on Migratory Species
DNVGL	Det Norske Veritas DNVGLand Germanischer Lloyd
dB	Decibel
EAP	Eastern Antarctic Peninsula
EE	Expert Elicitation
EEZ	Exclusive Economic Zone
EP	Protocol on Environmental Protection to the Antarctic Treaty
EIA	Environmental Impact Assessment
EU	European Union
FM	Frequency Modulated
HF	High Frequency
HRGS	High-Resolution Geophysical
Hz	Hertz
I	Impulsive
IEE	Initial Environmental Evaluation
IES	Initial Environmental Study
IR	Infrared
IUCN	International Union for Conservation of Nature
IWC	International Whaling Commission
kHz	Kilohertz
kW	Kilowatt
LF	Low Frequency
LS	Least Sensitive
L_{peak}	Peak Sound Pressure Level
MBES	Multi-Beam Echo-Sounder

Abbreviation	Explanation
MCDW	Modified Circumpolar Deep Water
MIZ	Marginal Ice Zone
MMO	Marine Mammal Observer
MS	Most Sensitive
MSL	Monopole Source Levels
NERC	Natural Environment Research Council
NI	Non-impulsive
NIHL	Noise-induced Hearing Loss
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
OBIS-SEAMAP	Ocean Biodiversity Information System Spatial Ecological Analysis of Megavertebrate Populations
OCA	Other Carnivores in Air
OCW	Other Carnivores in Water
PAM	Passive Acoustic Monitoring
PANGAEA	A data publishing service hosted by Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research, Center for Marine Environmental Sciences, University of Bremen
PBR	Potential Biological Removal
PCoD	Population Consequences of Disturbance
PCW	Phocids in Water
PTS	Permanent Threshold Shift
QGIS	Quantum Geographic Information System
RGB	Red Green Blue (visible spectrum)
RMS	Root Mean Square
RNL	Radiated Noise Levels
ROV	Remotely Operated Vehicle
RV	Research Vessel
sACCf	southern portion of the Antarctic Circumpolar Current front
SBP	Parametric Sub-Bottom Profiler
SEL	Sound Exposure Level
SEL_{cum}	Cumulative Sound Exposure Level
SHELF	Sheffield Elicitation Framework
SL	Source Level
SPL	Sound Pressure Level
SST	Sea Surface Temperature
TS	Threshold Shift
TTS	Temporary Threshold Shift
UAS	Unmanned Aerial Systems
UBA	German Environment Agency
US	United States
USBL	Ultra Short Baseline

Abbreviation	Explanation
VHF	Very High Frequency
WAP	Western Antarctic Peninsula

Summary

The States Parties to the Antarctic Treaty committed themselves to the comprehensive protection of the Antarctic environment and dependent and associated ecosystems and designated Antarctica as a natural reserve, devoted to peace and science (Article 2 of the Protocol on Environmental Protection to the Antarctic Treaty [EP]). All activities in the Antarctic, which are organised in Germany or proceed from its territory, require an official permit from the German Environment Agency (UBA) as the national competent authority designated by the Act Implementing the EP (AIEP). The EP protects native animals at a population level and native mammals and birds at the individual level, prohibiting activities that molest, handle, capture, injure or kill a native mammal or bird (Annex II, EP).

Anthropogenic noise can molest, injure or even lead to death of marine mammals (e.g. Richardson 1995, Southall et al. 2007). Therefore, applications to carry out activities in the Antarctic that lead to the emission of underwater noise are often categorised to have at least a minor or temporary impact on marine mammals. As a result, UBA need to conduct an Initial Environmental Evaluation (IEE) of applications based on an Initial Environmental Study (IES) provided by the applicant. Activities with less than a minor or transitory impact are subject to an Environmental Impact Assessment (EIA) based on the application. The main anthropogenic noise sources are ships, seismic airguns and hydroacoustic research equipment, and the noise impacts to consider from the EP-Annex II prohibited activities listed above are mainly behavioural impact (molesting) and auditory injury (henceforth in text ‚injury‘). However, no specific guidelines for noise emission in the Antarctic have yet been established (Erbe et al. 2019).

As many as twenty-six marine mammal species inhabit the waters south of 60°S: eight mysticete species, 12 odontocete species and six pinniped species, of which the conservation status according to the Red List of the International Union for Conservation of Nature (IUCN) ranges from ‘critically endangered’ (Antarctic blue whale) to ‘least concern’ (e.g. Leopard seal) (Erbe et al. 2019). Information on the distribution and abundance of the Antarctic marine mammal species is relatively scarce, as is information on the effect of noise on the species in this region. Absolute sound levels or dose-response relationships between noise levels and behavioural responses are often used to assess the risk of behavioural impact of noise on marine mammals (Tyack and Thomas 2019), which largely rely on studies and observations outside of the Antarctic (e.g. reviewed in Southall et al. 2007, Gomez et al. 2016). Multi-factor relationships make a predictive assessment of the behavioural impact of noise difficult (Ellison et al. 2012).

A variety of experimental studies have provided data on the impact of noise on the mammalian ear: the sound emitted by man-made sources can affect a marine mammal’s hearing sensitivity (i.e. increasing its hearing threshold) within certain frequency ranges. This threshold shift (TS) can be either temporary (TTS) or permanent (PTS). Exposure to loud, brief, transient sounds (impulsive sounds, such as explosions, airgun shots or pile strikes) is more damaging to the mammalian ear as it increases the hearing threshold faster than exposure to non-impulsive sound (such as from drilling and shipping), i.e. less sound energy is needed to induce TTS or PTS. Impulsive sound can induce a threshold shift either instantly, or through exposure to sound over time: high peak sound pressure levels (L_{peak}) can cause instant damage to the inner ear, and the accumulated sound energy the animal is exposed to (cumulative sound exposure levels, SEL_{cum}) over the entire duration of a discrete or repeated noise exposure has the potential to induce auditory damage if it exceeds distinct threshold levels. For impulsive sound, Southall et al. (2019) propose the use of a “dual-criterion”: one noise threshold based on the metric L_{peak} (unweighted), and one on the SEL_{cum}, weighted with a species group specific weighting curve,

which is based on the hearing thresholds of the group's species (grouped into, e.g. low-frequency (baleen whale species), high-frequency (dolphin species), very high frequency (porpoise species) cetaceans, and phocid seals in air and in water). For non-impulsive sound, only a species group specific weighted SEL_{cum} threshold value is proposed; the L_{peak} does not need to be considered.

Therefore, the objective of the "Detrimental effects of underwater noise – Development of the basics for a noise protection concept for Antarctica" was to generate new noise thresholds to support impact assessments. The project developed a series of short studies to support two Expert Elicitation (EE) workshops designed to generate noise thresholds for both behavioural responses (‚molest'), and auditory injury (‚injury'), of marine mammals in Antarctica in relation to their exposure to noise stressors including vessel noise, seismic airguns and hydroacoustic research equipment. The objective of the project was to develop this criteria matrix. To achieve this, the following approach was undertaken.

A series of short studies were carried out to capture the current state of scientific knowledge around the scope of the project. These included summarising the noise sources under consideration in Antarctica, the marine mammal species that should be scoped in or out of the project, the current state of knowledge on marine mammal behavioural responses and auditory injury and mitigation. These provided the foundations for expert workshops designed to generate new noise thresholds from which the criteria matrix would be derived. This process also involved the development of mitigation studies and guidance documents for how these outputs could be best implemented. A final conference was designed to disseminate the work carried out in this project and to stimulate engagement from stakeholders.

Expert elicitation is a well-established technique for use in data-deficient situations in which there is a pressing management or conservation need (Runge et al. 2011, Martin et al. 2012). The EE techniques can be implemented to both translate and combine information obtained from a group of experts with ranging backgrounds and expertise, into quantitative statements. A critical component of this technique is that the elicitation must be designed and facilitated in a manner that ensures that biases, such as social dominance, anchoring and others are minimised (Morgan 2014). The expert elicitation approach utilised in this study followed the concepts outlined in the Sheffield Elicitation Framework (SHELF) (Astfalck et al. 2018, Gosling 2018).

Two panels of experts were invited to participate in the process, with varying backgrounds in behavioural response studies or auditory injury for a range of marine mammal species. Pre-workshop webinars were hosted with the invited experts, and short studies (in both report and presentation formats) were provided to the experts to assist with summarising the information on the noise sources, Antarctic marine mammal species abundances and distributions, and a review of the current state of knowledge of behavioural responses of marine mammals to anthropogenic noise. For the purpose of the behavioural response elicitation, the experts elicited under a pre-defined and agreed definition of 'molest' or significant disturbance. This was defined by UBA as '*all actions and activities that either have an impact on individual fitness, a physiological impact or result in disruption to or interference with an organism's behavioural pattern or life processes, or that have a negative impact on the psychological well-being of the animal*'. In this context, 'molesting' is not necessarily consisting of physical contact with the animal. Noise stressors considered in the elicitation comprised:

- Vessels, used for both research and tourism purposes, with focus on Germany's research vessel (RV) *Polarstern*;
- Seismic airguns used from shipboard platforms for research purposes; and

- Hydroacoustic equipment operated from shipboard platforms including Hydrosweep, Parasound P70, and Posidonia 6000 active acoustic sources.

Marine mammal species were grouped according to their hearing groups as proposed by Southall et al. (2019). The behavioural response elicitation generated a series of noise thresholds for the most sensitive species of each Antarctic marine mammal species group and captured the current scientific uncertainty (represented by the spread in the distribution around the median). For each elicited distribution, the median provides the 'best estimate' and, therefore, the threshold to be used. These values represent the received level at which a significant response was predicted to occur in the average animal of the most sensitive species group (severity score 4+; sensu Southall et al. 2021). The spread of the distribution represents the marked scientific uncertainty around the received level at which the average animal in species groups responds but not the variation between individuals. Specifically, this means that the distributions presented here cannot be used to estimate the probability or likelihood that animals respond to a noise source.

For the injury elicitation, we looked to experts to estimate the amount of threshold shift (TS) that potentially causes injury in individuals of different marine mammal species groupings. UBA defines injury as '*significant (=non-negligible) damage to the physical integrity or health of each individual animal such as a temporary/reversible impairment*'. UBA considers TTS as a temporary/reversible impairment. Within the constraints of the elicitation, a diverse group of marine mammal experts estimated when the probability of a TS would significantly and negatively affect biological and/or life history functions of a marine mammal. We used a structured elicitation process to judge the relationship between the magnitude of threshold shift and when injury might occur in Antarctic marine mammal species groups exposed to different noise stressors. The distributions represent the current scientific uncertainty and the median, the best estimate of the TS considered significant (as defined here).

In order to derive absolute threshold values based on the median TS thresholds, the method of Southall et al. (2019) was used. While knowledge of noise induced hearing effects in marine mammals has increased greatly since 1994, further research, discussions and agreements are needed to improve noise impact assessments and reduce uncertainties.

The elicitation approach provided a formal mechanism to provide scientific advice based on limited available data, on quantities of interest to regulators. This study provided the starting point for addressing key issues in the impact assessment process, through the derivation of single threshold distributions across three noise stressors in Antarctic waters, for all marine mammal species found within this region. This allowed the provision of scientific advice for a pressing management issue through quantifying the experts' uncertainty around the evidence, partly arising from substantial data gaps. Going forward, it was recommended that data on the specific noise stressors in Antarctica and species response to it will significantly improve the knowledge base and help improve uncertainty. Once further data is available considering the probabilistic nature of response is captured in future behavioural response functions.

A separate internal UBA report (summarised herein) provides guidance on what to consider when evaluating the environmental impact of anthropogenic noise within the EIA or IEE and proposes a set of noise thresholds to be used in order to determine impact ranges around Antarctic noise sources (based on the output of the elicitations). These noise thresholds help to quantify the impacts of a significant behavioural response ("molest") by or injury to an individual of a marine mammal species. For assessing the noise impact on Antarctic marine mammals of an intended activity (according to the requirements of the EP and AIEP), we propose to follow the steps in a framework and described in further detail in that report. This report covers the following and provides recommendations of how decisions by the competent authority can be robustly made under the EP.

- Source activity specific information

  - Area as well as duration and time of activity,
  - Noise sources operated in the activity area and characterisation of their noise emission,
  - Marine mammal species that may occur in the area during the time of activity and associated information,
- Conduct noise modelling specific to the activity area and the noise emission of the noise sources,
- Select noise thresholds specific to the marine mammal species and noise sources,
- Compute impact areas and/or ranges by applying the noise thresholds to the noise modelling output, considering the duration of the activity,
- Calculate the possibility of a marine mammal being molested or injured, and/or the number of animals potentially being exposed to the possible risk of molesting or injury, in cases where marine mammal density in the activity area is known or can be estimated,
- Evaluate the magnitude of the potential impact of the activity based on the results of the assessment, and
- Use the evaluation to decide on the permit application.

In addition to the noise thresholds, the larger assessment process (including mitigation) has been considered. This involved working through the legislative framework under which marine mammal populations in Antarctica are protected in mind, the current impact assessment and decision making processes, to map out future research needs. As a result a series of topic areas where future research can support further noise concept development are provided below.

Three key elements affecting the total number of animals being molested or injured (as defined here) are the underlying density estimates of animals around the source, the source characteristic and propagation of these sources and the thresholds at which animals are affected. This study has derived new thresholds with the best available information, but underlying density estimates and noise characteristics remain critical sensitivities affecting impact assessments. Therefore critical needs are:

- Improved abundance and density estimates (with estimates of uncertainty) for Antarctic species for times of year and regions most often impacted.
- Real-world measurements of the noise source characteristics and propagation of different sources in the Antarctica environment.
- Consideration of how noise emitted might be reduced to minimum levels required for research purposes (e.g. reduced source levels, only critical systems used on vessels).

Essential components of estimating impact, both for behavioural response (‘molest’) and injury as defined here, are the assumptions around the exposure of animals. In classic noise impact assessment approaches, the key factors in the model are distribution and dive depth of the animals during exposure events. Three-dimensional models which considers both horizontal and vertical movements can be too cumbersome to model. But a simplified model which only considers the vertical movement of an animal in a fixed position, can provide an appropriate solution to generate more precise impacts of a given anthropogenic activity. To continue to improve noise thresholds or noise impact assessment approaches (e.g. considering the probabilistic nature of response and the exposure of the animals), the following areas should be advanced.

- Controlled exposure experiments for priority Antarctic species, to help better parameterise thresholds for behavioural response to noise stressors in the Antarctic environment. In the long term, such studies can provide sufficient data to inform noise thresholds, including dose response thresholds (if considered appropriate within the legislative framework). In the short term, new empirical information can support improved decision making for updating fixed noise thresholds.
- Continuing experimental studies to improve knowledge about the hearing and threshold shift (and consequences of shifts) in Antarctic species (or their surrogates) will be invaluable to support improved thresholds in the future.
- Better knowledge on the horizontal and vertical movement patterns of Antarctic species to improve mapping of the occurrence and temporal and spatial overlap with activities which can be cross-reference with key periods for Antarctic species. This can inform movement models to improve estimates of exposure.
- Development of population consequences frameworks for the most important populations. Note: such frameworks require significant information to construct – but can provide a roadmap for evidence gaps and data needs.
- Finally, improved methods for monitoring of Antarctic species and the live mitigation of impacts to support the execution of research activities in a sustainable manner is advised. However any mitigation approaches must be proportionate and ideally not hinder the research activity.

Zusammenfassung

Die Vertragsstaaten des Antarktis-Vertrags haben sich zum umfassenden Schutz der antarktischen Umwelt sowie der abhängigen und verbundenen Ökosysteme verpflichtet und die Antarktis als Naturreservat ausgewiesen, das dem Frieden und der Wissenschaft gewidmet ist (Artikel 2 des Umweltschutzprotokolls zum Antarktis-Vertrag [USP]). Alle Tätigkeiten in der Antarktis, die in Deutschland organisiert werden oder vom deutschen Hoheitsgebiet ausgehen, bedürfen einer Genehmigung des Umweltbundesamtes (UBA) als nationaler zuständiger Behörde, die durch das Gesetz zur Ausführung des USP (AUG) benannt wurde. Das USP schützt einheimische Tiere auf Populationsebene und einheimische Säugetiere und Vögel auf Individuenebene, indem es verbietet, einheimische Säugetiere oder Vögel zu stören, zu berühren, zu fangen, zu verletzen oder zu töten (Annex II, USP).

Vom Menschen verursachter Lärm kann Meeressäuger stören, verletzen oder sogar zu deren Tod führen (z.B. Richardson 1995, Southall et al. 2007). Daher werden Tätigkeiten in der Antarktis, die Unterwasserlärm erzeugen, oft als Tätigkeiten eingestuft, die zumindest geringfügige oder vorübergehende Auswirkungen auf Arten von Meeressäugern oder deren Populationen haben. Deshalb muss das UBA eine Umwelterheblichkeitsprüfung (UEP) der Anträge auf der Grundlage einer Umwelterheblichkeitsstudie (UES) durchführen, die vom Antragstellenden vorzulegen ist. Tätigkeiten mit weniger als geringfügigen oder vorübergehenden Auswirkungen unterliegen einer Umweltprüfung (UP) auf der Grundlage des Antrags. Die Hauptquellen für anthropogenen Lärm sind Schiffe, seismische Luftkanonen und hydroakustische Forschungsausrüstung. Die Lärmauswirkungen, die aufgrund der oben aufgeführten verbotenen Tätigkeiten gemäß USP-Annex II zu berücksichtigen sind, betreffen hauptsächlich Verhaltensreaktionen (Störung) und Hörschäden (Verletzung). Allerdings wurden bislang noch keine spezifischen Richtlinien für Lärmemissionen in der Antarktis festgelegt (Erbe et al. 2019).

Bis zu sechsundzwanzig Meeressäugerarten kommen in den Gewässern südlich von 60°S vor: Acht Arten von Bartenwalen, zwölf Arten von Zahnwalen und sechs Arten von Robben. Der Schutzstatus dieser Arten gemäß der Roten Liste gefährdeter Arten der Internationalen Union zur Bewahrung der Natur (IUCN) reicht von ‚vom Aussterben bedroht‘ (Antarktischer Blauwal) bis ‚nicht gefährdet‘ (z.B. Seeleopard) (Erbe et al. 2019). Informationen über die Verbreitung und Häufigkeit der antarktischen Meeressäugerarten sowie über die Auswirkungen von Lärm auf diese Arten sind kaum vorhanden. Absolute Schallpegel oder Dosis-Wirkungs-Beziehungen zwischen Lärmpegeln und Verhaltensreaktionen werden oft verwendet, um das Risiko von Lärmwirkungen auf Meeressäuger zu bewerten (Tyack und Thomas 2019). Diese stützen sich weitgehend auf Studien und Beobachtungen außerhalb der Antarktis (z.B. besprochen in Southall et al. 2007, Gomez et al. 2016). Zusammenhänge, die von mehreren Faktoren beeinflusst werden, erschweren eine prädiktive Bewertung der durch Lärm hervorgerufenen Verhaltensänderungen (Ellison et al. 2012).

Eine Vielzahl von experimentellen Studien hat Daten über die Auswirkungen von Lärm auf das Gehör von Säugetieren geliefert: Der von anthropogenen Quellen abgegebene Schall kann die Hörempfindlichkeit eines Meeressäugers in bestimmten Frequenzbereichen beeinträchtigen (d.h. die Hörschwelle erhöhen). Diese Schwellenwertverschiebung (*threshold shift*, TS) kann entweder vorübergehend (*temporary threshold shift*, TTS) oder permanent (PTS) sein. Die Einwirkung von lauten, kurzen, vorübergehenden Geräuschen (impulsive Geräusche wie Explosionen, Luftkanonenschüsse oder Pfahlschläge) lässt die Hörschwelle schneller ansteigen und ist somit schädlicher für das Gehör von Säugetieren als nicht impulsiver Lärm (z.B. von Bohrungen und Schiffsverkehr). Das bedeutet, es wird weniger Schallenergie benötigt, um eine

TTS oder PTS hervorzurufen. Impulsschall kann entweder sofort oder durch längere Exposition eine Schwellenwertverschiebung hervorrufen: Hohe Spitzenschalldruckpegel (L_{peak}) können sofortige Schäden am Innenohr verursachen und die angesammelte Schallenergie, der ein Tier während einer einzelnen oder wiederholten Lärmexposition ausgesetzt ist (kumulative Schallbelastungspegel, SEL_{cum}), kann Hörschäden verursachen, wenn sie bestimmte Grenzwerte überschreitet. Für impulsiven Schall schlagen Southall et al. (2019) die Verwendung eines "Doppelkriteriums" vor: ein Schwellenwert basierend auf L_{peak} (ungewichtet) und ein Schwellenwert basierend auf SEL_{cum}, gewichtet nach einer artgruppenspezifischen Gewichtungskurve, die auf den Hörschwellen der Arten der Gruppe basiert (unterteilt in z.B. niederfrequente Bartenwalarten, hochfrequente Delfinarten, sehr hochfrequente Schweinswalarten sowie Hundsrobben in Luft und im Wasser). Für nicht impulsiven Schall wird nur ein artgruppenspezifischer gewichteter SEL_{cum}-Schwellenwert vorgeschlagen; L_{peak} muss nicht berücksichtigt werden.

Das Ziel des Projekts „Schädliche Auswirkungen von Unterwasserlärm – Entwicklung der Grundlagen für ein Lärmschutzkonzept für die Antarktis“ war daher die Festlegung neuer Lärmgrenzwerte sowohl für Verhaltensreaktionen (Störung) als auch für Hörschäden (Verletzung) von Meeressäugern in der Antarktis, insbesondere in Bezug auf ihre Belastung durch verschiedene Lärmquellen wie Schiffsgeräusche, seismische Luftkanonen und hydroakustische Forschungsausrüstung. Um diese Kriterienmatrix zu erhalten, wurde der folgende Ansatz verfolgt.

Im Rahmen des Projekts wurden verschiedene Kurzstudien durchgeführt, um den derzeitigen Stand der wissenschaftlichen Erkenntnisse zu erfassen. Dabei wurden die in der Antarktis vorkommenden Lärmquellen erfasst, die betroffenen Meeressäugerarten identifiziert und der aktuelle Kenntnisstand bezüglich der Verhaltensreaktionen von und Hörschäden bei Meeressäugern zusammengefasst. Ebenfalls wurden Strategien zur Lärmreduktion und deren Auswirkungen betrachtet. Basierend auf diesen Informationen wurden Experten-*Elicitation*-Workshops organisiert, mit dem Ziel, neue Lärmgrenzwerte festzulegen, aus denen die Kriterienmatrix abgeleitet wurde. Weiterhin wurde eine Kurzstudie zur Lärmreduktion durchgeführt sowie Leitfäden erstellt, um die gewonnenen Erkenntnisse optimal umzusetzen. Zum Abschluss fand eine Konferenz statt, bei der die Ergebnisse des Projekts vorgestellt und ein Austausch mit relevanten Interessensgruppen angeregt wurde.

Die Experten-*Elicitation* ist eine etablierte Methode, die in Situationen eingesetzt wird, in denen es an Daten mangelt, jedoch ein dringender Handlungsbedarf bezüglich Management oder Naturschutz besteht (Runge et al. 2011, Martin et al. 2012). Mit dieser Methode lassen sich Informationen von Experten unterschiedlicher Fachgebiete in quantitative Aussagen überführen und vereinigen. Ein kritischer Aspekt dieser Methode ist die Notwendigkeit, die *Elicitation* so zu gestalten und durchzuführen, dass Einflüsse wie soziale Dominanz oder der Ankereffekt minimiert werden (Morgan 2014). Der in dieser Studie angewandte Ansatz der Experten-*Elicitation* basiert auf den im *Sheffield Elicitation Framework* (SHELF) beschriebenen Konzepten (Astfalck et al. 2018, Gosling 2018).

Zwei Gruppen von Fachexperten, die sich auf Verhaltensreaktionen und akustische Schäden bei Meeressäugern spezialisiert haben, wurden zur Teilnahme eingeladen. Im Vorfeld der Workshops fanden Webinare für die eingeladenen Experten statt. Ihnen wurden zudem Kurzstudien in Form von Berichten und Präsentationen bereitgestellt. Diese Unterlagen boten einen Überblick über die Lärmquellen, die Verteilung und Häufigkeit antarktischer Meeressäuger und den aktuellen Kenntnisstand bezüglich der Verhaltensreaktionen von Meeressäugern auf anthropogenen Lärm. Für die Bewertung der Verhaltensreaktionen orientierten sich die Experten an einer zuvor festgelegten und abgestimmten Definition von

'Störung'. Das UBA definierte dies als *„alle Handlungen und Tätigkeiten, die die individuelle Fitness beeinflussen, physiologische Effekte verursachen, die Verhaltensmuster oder Lebensprozesse eines Organismus stören oder beeinträchtigen oder sich negativ auf das psychische Wohlbefinden des Tieres auswirken"*. In diesem Kontext bedeutet Störung nicht zwangsläufig physischen Kontakt mit dem Tier. Bei der Experten-*Elicitation* berücksichtigte Lärmstressoren beinhalten:

- Schiffe, sowohl für Forschungs- als auch für Tourismuszwecke verwendet, mit besonderem Augenmerk auf Deutschlands Forschungsschiff *Polarstern*;
- Seismische Luftkanonen, die von Schiffsplattformen für Forschungszwecke eingesetzt werden; und
- Hydroakustische Geräte, die von Schiffsplattformen betrieben werden, einschließlich der aktiven akustischen Quellen Hydrosweep, Parasound P70 und Posidonia 6000.

Die Meeressäugerarten wurden gemäß ihrer Gehörgruppen kategorisiert, wie von Southall et al. (2019) vorgeschlagen. Die Elicitation der Verhaltensreaktionen lieferte eine Reihe von Lärmgrenzwerten für die empfindlichsten Arten jeder Gruppe antarktischer Meeressäuger. Dabei wurde die aktuelle wissenschaftliche Unsicherheit berücksichtigt, die durch die Streuung rund um den Median dargestellt wird. Bei jeder dieser Verteilungen stellt der Median die beste Schätzung dar und ist somit der zu nutzende Grenzwert. Diese Werte zeigen den Schallpegel auf, bei dem eine signifikante Reaktion eines repräsentativen Individuums der empfindlichsten Artengruppe erwartet wird (Schweregrad 4+; laut Southall et al. 2021). Die Streuung der Verteilung verdeutlicht die ausgeprägte wissenschaftliche Unsicherheit hinsichtlich des Schallpegels, ab dem die repräsentativen Tiere einer Artengruppen reagieren, nicht jedoch die Variation zwischen den Individuen. Das bedeutet konkret, dass die hier dargestellten Verteilungen nicht dazu verwendet werden können, die Wahrscheinlichkeit oder das Risiko zu bestimmen, dass Tiere auf eine Lärmquelle reagieren.

Bei der *Elicitation* zu potenziellen Hörschäden wurde von Experten für Meeressäuger der Grad der Schwellenwertverschiebung (TS) ermittelt, der möglicherweise bei verschiedenen Gruppierungen von Meeressäugerarten zu Verletzungen führt. Das UBA definiert eine Verletzung als *„signifikante (= nicht zu vernachlässigende) Schädigung der körperlichen Unversehrtheit oder Gesundheit jedes einzelnen Tieres, wie beispielsweise eine vorübergehende/reversible Beeinträchtigung"*. Das UBA betrachtet TTS als vorübergehende/reversible Beeinträchtigung. Vor diesem Hintergrund schätzte die Expertengruppe den Zeitpunkt ab, wann die Wahrscheinlichkeit einer TS die biologischen und/oder lebenswichtigen Funktionen eines Meeressäugers erheblich und nachteilig beeinflussen würde. Wir führten strukturierte Gespräche mit den Experten durch, um das Verhältnis zwischen der Höhe der Schwellenwertverschiebung und dem Zeitpunkt zu bewerten, zu dem Verletzungen bei antarktischen Meeressäugerarten auftreten könnten, die verschiedenen Lärmstressoren ausgesetzt sind. Die Verteilungen repräsentieren die aktuelle wissenschaftliche Unsicherheit, wobei der Median die beste Schätzung für die als signifikant erachtete TTS darstellt (wie hier definiert).

Um absolute Grenzwerte basierend auf den Medianen der Schwellenwertverschiebung zu ermitteln, wurde die Methode von Southall et al. (2019) angewendet. Obwohl das Wissen über die durch Lärm verursachten Höreffekte bei Meeressäugern seit 1994 erheblich zugenommen hat, sind weitere Forschung, Diskussionen und Vereinbarungen erforderlich, um Lärmfolgenabschätzungen zu verbessern und Unsicherheiten zu reduzieren.

Der *Elicitation*-Ansatz bot eine strukturierte Methode zur Bereitstellung wissenschaftlicher Empfehlungen auf Basis begrenzter verfügbarer Daten zu Größen, die für die Regulierungsbehörden relevant sind. Dies half, zentrale Fragen im Prozess der Folgenabschätzung anzugehen, indem Verteilungen von Grenzwerten für drei Lärmstressoren in den Gewässern der Antarktis für sämtliche Meeressäugerarten dieser Region ermittelt wurden. Dadurch konnte wissenschaftlich fundierter Rat zu einem drängenden Problem gegeben werden, wobei die Unsicherheit der Experten hinsichtlich der verfügbaren Beweise, die teilweise auf erheblichen Datenlücken beruhte, quantifiziert wurde. Für die Zukunft wird empfohlen, die Erfassung von Daten zu den spezifischen Lärmquellen in der Antarktis und deren Auswirkungen auf die Arten zu fördern, um die wissenschaftliche Grundlage zu stärken und Unsicherheiten zu reduzieren. Sobald weitere Daten verfügbar sind, sollte die probabilistische Natur der Verhaltensreaktion in zukünftigen Beurteilungen berücksichtigt werden.

Ein separat erstellter interner Leitfaden des UBA, der in diesem Bericht zusammengefasst wird, bietet Leitlinien zur Bewertung der Umweltauswirkungen von anthropogenem Lärm im Rahmen der UP oder UEP. In diesem Leitfaden werden auch Grenzwerte für Lärmbelastungen vorgeschlagen, um den Bereich zu definieren, in dem antarktische Lärmquellen möglicherweise Auswirkungen auf Meeressäuger haben könnten. Diese Vorschläge basieren auf den Ergebnissen der Experten-*Elicitation* und dienen der Quantifizierung der Auswirkungen einer signifikanten Verhaltensreaktion (Störung) oder Verletzung eines Individuums einer Meeressäugerart. Zur Bewertung des Lärmeinflusses auf antarktische Meeressäuger im Zusammenhang mit beabsichtigten Tätigkeiten gemäß USP und AUG empfehlen wir, die im Leitfaden beschriebenen Schritte zu befolgen. Dieser behandelt verschiedene Aspekte und bietet Empfehlungen für die zuständigen Behörden, um Entscheidungen gemäß dem USP auf fundierte Weise zu treffen.

- Bereitstellung von spezifischen Informationen zur Tätigkeit,
  - Gebiet sowie Dauer und Zeitpunkt der Tätigkeit,
  - Charakterisierung der Lärmemissionen der im Tätigkeitsgebiet vorhandenen Lärmquellen,
  - Informationen zu den Meeressäugerarten, die während der Tätigkeit in dem Gebiet vorkommen können,
- Durchführung einer speziell auf das Tätigkeitsgebiet und die Emissionen der vorhandenen Lärmquellen zugeschnittenen Lärmmodellierung,,
- Auswahl von Lärmgrenzwerten entsprechend der vorkommenden Meeressäugerarten und Lärmquellen,
- Berechnung der Wirkungsbereiche und/oder -reichweiten durch Anwendung der Lärmgrenzwerte auf die Ergebnisse der Lärmmodellierung unter Berücksichtigung der Tätigkeitsdauer,
- Berechnung der Wahrscheinlichkeit der Störung oder Verletzung von Meeressäugern und/oder der Anzahl potenziell betroffener Tiere, sofern die Meeressäugerdichte im Tätigkeitsgebiet bekannt oder abschätzbar ist,
- Bewertung des Ausmaßes der potenziellen Auswirkungen der Tätigkeit auf Grundlage der zuvor ermittelten Ergebnisse, und
- Verwendung der Bewertung zur Entscheidung über den Genehmigungsantrag.

Zusätzlich zu den Lärmgrenzwerten wurde auch der umfassendere Bewertungsprozess, einschließlich möglicher Maßnahmen zur Verringerung der Auswirkungen, berücksichtigt. Dabei wurde der rechtliche Rahmen für den Schutz der antarktischen Meeressäugerpopulationen sowie die aktuellen Prozesse zur Bewertung und Entscheidungsfindung im Auge behalten, um zukünftigen Forschungsbedarf zu ermitteln. Im

Ergebnis werden unten einige Forschungsbereiche aufgeführt, in denen zukünftige Studien zur Weiterentwicklung der Lärmschutzkonzepte beitragen können.

Drei entscheidende Faktoren, die sich auf die Gesamtzahl der gestörten oder verletzten Tiere (wie hier definiert) auswirken, sind die zugrunde liegenden Schätzungen der Tierdichte in der Nähe der Lärmquelle, die Eigenschaften dieser Quelle und die Ausbreitung des Lärms sowie die Grenzwerte, ab denen Tiere betroffen sind. Obwohl in diesem Projekt neue Grenzwerte unter Verwendung der besten verfügbaren Informationen abgeleitet wurden, bleiben die zugrunde liegenden geschätzten Tierdichten und die Charakteristika des Lärms entscheidende Faktoren, die die Folgenabschätzung beeinflussen. Drängende Forschungsbedarfe sind daher:

- Verbesserte Abundanz- und Dichteschätzungen (einschließlich der Unsicherheiten) für antarktische Arten, insbesondere für die am stärksten betroffenen Jahreszeiten und Gebiete.
- Reale Messungen der Eigenschaften von verschiedenen Lärmquellen und ihrer Auswirkungen auf die antarktische Umwelt.
- Überlegungen zur Reduzierung von Lärmemissionen auf das für Forschungszwecke erforderliche Minimum, wie beispielsweise die Senkung der Pegel von Lärmquellen oder die ausschließliche Nutzung kritischer Systeme auf Schiffen.

Die Abschätzung der Auswirkungen, sowohl für Verhaltensreaktionen (Störung) als auch für Verletzungen von Meeressäugern, hängt wesentlich von den Annahmen rund um die Lärmexposition der Tiere ab. Bei herkömmlichen Ansätzen zur Lärmfolgenabschätzung sind die Verteilung der Tiere und ihre Tauchtiefe während solcher Ereignisse entscheidende Faktoren. Die Verwendung von dreidimensionalen Modellen, die sowohl horizontale als auch vertikale Bewegungen berücksichtigen, kann aufgrund ihrer Komplexität herausfordernd sein. Daher kann ein vereinfachtes Modell, das sich auf die vertikale Bewegung eines Tieres in einer festen Position konzentriert, eine geeignete Lösung sein, um die Auswirkungen einer bestimmten anthropogenen Tätigkeit genauer zu bewerten. Um die Genauigkeit der Lärmgrenzwerte oder der Ansätze zur Bewertung der Lärmauswirkungen weiter zu erhöhen, insbesondere unter Berücksichtigung der wahrscheinlichen Lärmexpositionen der Tiere und ihrer Reaktionen darauf, sollten die folgenden Bereiche weiterentwickelt werden.

- Kontrollierte Expositionsexperimente für prioritäre antarktische Arten können dazu beitragen, die Grenzwerte für Verhaltensreaktionen auf Lärmstressoren in der Antarktis genauer zu bestimmen. Langfristig könnten solche Untersuchungen ausreichende Daten zur Festlegung von Lärmgrenzwerten bereitstellen, einschließlich Dosis-Wirkungs-Grenzwerten, sofern dies im Rahmen der gesetzlichen Bestimmungen als angemessen erachtet wird. In der Zwischenzeit können neue empirische Erkenntnisse dazu beitragen, die Aktualisierung der festgelegten Lärmgrenzwerte zu verbessern.
- Die Fortführung experimenteller Studien zur Verbesserung des Wissens über das Gehör und die Schwellenwertverschiebung des Gehörs bei antarktischen Arten oder ihren Vertreterarten ist von unschätzbarem Wert, um in Zukunft präzisere Grenzwerte zu ermitteln.
- Bessere Kenntnisse über die horizontalen und vertikalen Bewegungsmuster antarktischer Arten sind erforderlich, um ihr zeitliches und räumliches Vorkommen besser mit Tätigkeiten in wichtigen Zeiträumen für diese Arten abzustimmen. Diese Erkenntnisse könnten in Bewegungsmodelle einfließen, um die Expositionsschätzungen zu verbessern.
- Erarbeitung von Plänen zur Bewertung der Auswirkungen auf Populationen wichtiger Tiergruppen. Es ist wichtig zu beachten, dass die Entwicklung solcher Pläne umfangreiche

Informationen erfordert, jedoch dazu beitragen kann, einen Fahrplan für bestehende Wissenslücken und den Bedarf an weiteren Daten zu erstellen.

- Abschließend wird empfohlen, verbesserte Überwachungsmethoden für antarktische Arten sowie Maßnahmen zur Minderung der Auswirkungen von Lärm auf die Umwelt zu entwickeln, um die Durchführung von Forschungstätigkeiten auf nachhaltige Weise zu unterstützen. Diese Maßnahmen müssen jedoch verhältnismäßig sein und dürfen die Forschungstätigkeit vorzugsweise nicht beeinträchtigen.

1 Introduction

The States Parties to the Antarctic Treaty committed themselves to the comprehensive protection of the Antarctic environment and dependent and associated ecosystems and designated Antarctica as a natural reserve, devoted to peace and science (Article 2 of the Protocol on Environmental Protection to the Antarctic Treaty [EP]). All activities in the Antarctic, which are organised in Germany or proceed from its territory, require an official permit from the German Environment Agency (UBA) as the national competent authority designated by the Act Implementing the EP (AIEP). The EP protects native animals at population level and native mammals and birds at individual level, prohibiting activities that molest, handle, capture, injure or kill a native mammal or bird (Annex II, EP). Anthropogenic noise can molest, injure or even lead to the death of marine mammals (e.g. Richardson 1995, Southall et al. 2007).

Therefore, applications to carry out activities in the Antarctic that lead to the emission of underwater noise are often categorised to have at least a minor or temporary impact on marine mammal species or their populations. As a result, UBA need to conduct an Initial Environmental Evaluation (IEE) of applications based on an Initial Environmental Study (IES) provided by the applicant. Activities with less than a minor or transitory impact are subject to an Environmental Impact Assessment (EIA) based on the application. The main anthropogenic noise sources are ships, seismic airguns and hydroacoustic research equipment, and the noise impacts to consider from the in Annex II of the EP prohibited activities listed above are mainly behavioural impact (molesting) and auditory injury (henceforth in text ‚injury'). However, no specific guidelines for noise emission in the Antarctic have yet been established (Erbe et al. 2019).

As many as twenty-six marine mammal species inhabit the waters south of 60°S: eight mysticete species, 12 odontocete species and six pinniped species, of which the conservation status according to the Red List of the International Union for Conservation of Nature (IUCN) ranges from ‘critically endangered’ (Antarctic blue whale) to ‘least concern’ (e.g. Leopard seal) (Erbe et al. 2019). Information on the distribution and abundance of the Antarctic marine mammal species is relatively scarce, as is information on the effect of noise on the species in this region. Absolute sound levels or dose-response relationships between noise levels and behavioural responses are often used to assess the risk of behavioural impact of noise on marine mammals (Tyack and Thomas 2019), which largely rely on studies and observations outside of the Antarctic (e.g. reviewed in Southall et al. 2007, Gomez et al. 2016). Noise levels eliciting behavioural responses are often described in terms of the unweighted broadband sound levels received by an animal (Southall et al. 2007), although sound levels as perceived by the animal (weighted sound levels) might be a better predictor (Tougaard et al. 2015). Factors other than received sound level, including the activity state of animals or the spatial relationship between sound source and receiving animals may also affect the probability of a behavioural response (Ellison et al. 2012, Gomez et al. 2016, Dunlop et al. 2017). These multi-factor relationships make a predictive assessment of the behavioural impact of noise difficult (Ellison et al. 2012).

A variety of experimental studies have provided data on the impact of noise on the mammalian ear: the sound emitted by man-made sources can affect a marine mammal’s hearing sensitivity (i.e. increasing its hearing threshold) within certain frequency ranges. This threshold shift can be either temporary (TTS) or permanent (PTS). Exposure to loud, brief, transient sounds (impulsive sounds, such as explosions, airgun shots or pile strikes) is more damaging to the mammalian ear – as it increases the hearing threshold faster – than exposure to non-impulsive sound (such as from drilling and shipping), i.e. less sound energy is needed to induce TTS or PTS. Impulsive sound can induce a threshold shift either instantly, or through exposure to sound over time: high peak sound pressure levels (L_{peak}) can cause instant damage to the inner ear, and the accumulated sound energy the animal is exposed to (cumulative sound exposure levels, SEL_{cum}) over the entire duration of a discrete or repeated noise exposure has the potential to induce auditory damage if it exceeds distinct threshold levels. For SEL_{cum}, the magnitude of hearing impairment is best predicted by the received sound energy weighted for the species' hearing ability, while L_{peak} needs to be considered unweighted (Finneran 2015). Southall et al. (2019) propose noise exposure criteria to assess how much noise a marine mammal can be exposed to before it is at risk of experiencing this kind of injury. The criteria take into account that some species groups are more sensitive to noise than others, that the species' hearing abilities influence the possibility of injury, and the impulsiveness of sound. For impulsive sound, Southall et al. (2019) propose the use of a "dual-criterion": one noise threshold based on the metric L_{peak} (unweighted), and one on the SEL_{cum}, weighted with a species group specific weighting curve, which is based on the hearing thresholds of the group's species (grouped into, e.g. low-frequency (baleen whale species), high-frequency (dolphin species), very high frequency (porpoise species) cetaceans, and phocid seals in air and in water). For non-impulsive sound, only a species group specific weighted SEL_{cum} threshold value is proposed; the L_{peak} does not need to be considered.

While the development of noise thresholds for injury are further developed than those for behavioural impact, there are still several uncertainties that complicate the assessment of the risk of injury. For example:

- Southall et al. (2019) acknowledges that, as a result of propagation effects, the signal of certain sound sources loses its impulsive characteristics and could potentially be characterised as non-impulsive beyond a certain distance. The changes in noise characteristics with distance generally result in exposures becoming less physiologically damaging with increasing distance as sharp transient peaks become less prominent (Southall et al. 2007). The Southall et al. (2019) updated criteria proposed that, while keeping the same source categories, the exposure criteria for impulsive and non-impulsive sound should be applied based on the signal features likely to be received by the animal rather than those emitted by the source. Methods to estimate the distance at which the transition from impulsive to non-impulsive noise are currently being developed (Hastie et al. 2019a, Southall et al. 2019).

- To determine the SEL_{cum}, the received levels at the animal need to be estimated. This estimate depends on the distance of the animal to the sound source and the propagation loss of the sound while propagating away from the sound source. Assumptions relating to animal movement during exposure in relation to the sound source are therefore important to consider in the risk assessment, as well as an appropriate estimate of the sound levels at source and the propagation loss (Faulkner et al. 2018). The acoustic environment in Antarctic waters is, however, more complicated than in most other regions, mainly through the prevailing ice cover (Erbe et al. 2019), which make the predictions of noise propagation more difficult for this area.

The lack of agreed noise thresholds and noise impact assessment procedures makes it difficult to conduct and evaluate impact assessments of activities in the Antarctic in a standardised and therefore comparable manner. The scarcity of data on marine mammal species abundance and distribution further increases the uncertainty in any prediction of the number of animals that might be at risk of impact. In an UBA expert workshop held in November 2018 in Berlin, Germany, stakeholders identified a need to improve the criteria that have been used by UBA in the past, and therefore recommended a refinement of noise exposure criteria for the Antarctic region, with clear application guidance for noise impact assessments, better data on Antarctic marine mammal abundance and distribution, better data on their hearing ability (especially for mysticetes), and an assessment of the effectiveness of various noise mitigation options (Erbe et al. 2019). The effectiveness of noise reduction systems as well as that of monitoring methods to mitigate marine mammal noise impact depend on the environmental conditions they are applied in as well as the species under consideration (Verfuss et al. 2018, Verfuss et al. 2019a, Verfuss et al. 2019b).

One of the conclusions of this workshop was to recommend focused international expert workshops to develop a criteria matrix specifically for Antarctic marine mammal species and the main anthropogenic sound sources as a basis for a noise protection concept for Antarctica, and to discuss mitigation measures.

1.1 Scope of work

Therefore, the objective of the "Detrimental effects of underwater noise – Development of the basics for a noise protection concept for Antarctica" was to generate new noise thresholds to support impact assessments. The project developed a series of short studies to support two expert elicitation workshops designed to generate noise thresholds for both behavioural responses (‚molest'), and auditory injury (‚injury'), of marine mammals in Antarctica in relation to their exposure to noise stressors including vessel noise, seismic airguns and hydroacoustic research equipment.

The objective of the project was to develop this criteria matrix. To achieve this, the following approach was undertaken.

A series of short studies were carried out to capture the current state of scientific knowledge around the scope of the project. These included summarising the noise sources under consideration in Antarctica, the marine mammal species that should be scoped in or out of the project, the current state of knowledge on marine mammal behavioural responses and auditory injury. These provided the foundations for expert workshops designed to generate new noise thresholds from which the criteria matrix would be derived. This process also involved the development of mitigation studies and guidance documents for how these outputs could be best implemented. A final conference was designed to disseminate the work carried out in this project and to stimulate engagement from stakeholders.

1.2 Report structure

This report summarises the outputs of this process. The remainder of the report following the following structure: Chapter 2 outlines the short studies that support the two expert elicitation exercises (used to develop the required noise thresholds). The following annexes provide additional details beyond those presented in Chapter 2:

- Annex 1 – Noise source short study
- Annex 2 – Marine mammal short study
- Annex 3 – Behavioural response short study
  - Annex 3 – Supplements A, B and C (downloadable from the UBA publication site)
- Annex 4 – Auditory injury short study
- Annex 5 – Mitigation short study

Chapters 3 and 4 summarise the process undertaken and the results of the expert elicitation exercises. Chapter 5 summarises how these new thresholds can be implemented in an impact assessment process and highlight other elements that can be advanced. Chapter 6 summarises the final conference of the project, which provided a forum for discussing the noise concept and constituent parts and how it can be iteratively improved. Chapter 7 provides conclusions and recommendations in support of advancing the noise concept described herein.

2 Short study summaries

A series of short studies, developed to support the development of a noise protection concept for Antarctica, were carried out. They are described in this chapter.

2.1 Review of anthropogenic underwater noise sources commonly used for research in Antarctica

Authors: Schuster, M. & Erbe, C.

This chapter details the typical anthropogenic noise sources in the Antarctic and provide noise propagation modelling results for these anthropogenic sources. These results can be used to estimate the sound levels that marine mammals are exposed to from various anthropogenic sources. The report considers three anthropogenic noise sources typically found in the Antarctic region: vessels, seismic airguns, and hydroacoustic research equipment (Hydrosweep, Parasound P70, and Posidonia 6000). Noise propagation was modelled for two Antarctic habitat types: a deep water, flat-bottomed habitat and a shallow coastal marine environment.

Ships emit continuous noise in a broad range of frequencies from 10 Hz to 100 kHz. Noise emitting sources on board a vessel may include propeller cavitation, the noise radiation of the main engine, generator engines and gearbox, the airborne noise produced by various machinery, and the noise associated with the breaking bow wave. Ship noise level was described by a one source level spectrum summarising these contributions. The RV *Polarstern*, an icebreaker vessel frequently used for German research activities, was selected for modelling omni directional propagation in Antarctic waters. This vessel produces a high source level even when at a reduced speed (6 knots) due to the tendency of the controllable pitch propellers to cavitate when the pitch is reduced. This is expected to be a dominant noise source even when the ship is stationary.

The main options presented for mitigating ship noise are:

- Operational measures, such as adjusting the speed when sailing in sensitive habitats.
- Technical modifications of the vessel (installing sound-masking measures).
- Vessel designs incorporating noise control (propeller design focused on avoidance of cavitation).

Seismic airguns are filled with compressed air which is released suddenly into the water, producing impulsive pressure waves. This low-frequency impulsive noise is used for the investigation of sub-bottom structures under the seabed. Additional noise associated with seismic airguns results from the rattling of components and bubble cavitation.

Quantifying the noise emitted by seismic airguns requires measuring the full airgun array geometry, the towing depth, the firing pressure, and the airgun specifications. In general, the shallower the towing, the higher the concentration of low-frequency acoustic energy towards the bottom, as the low-frequency component of the signal is affected by the Lloyd's Mirror effect.

Two forms of mitigation are presented for seismic airgun noise:

- Optimizing the airgun array: adjusting the firing pressure and minimizing sideward radiation by adjusting the towing depth.
- Increasing the inter-pulse interval.

The Hydrosweep is a multibeam echosounder used to map the bathymetry of the sea floor. It consists of a transducer that radiates focused acoustic energy in a downward and transverse direction. This makes it a highly directional sound source; it produces short burst signals consisting of frequency modulated tones at frequencies between 13 kHz and 17 kHz. The parameters that can be configured for Hydrosweep operations are the source level, the repetition rate, the working frequency, the pulse length, and the number of active beams. All of these characteristics influence the noise emission.

The mitigation options that can reduce noise associated with Hydrosweep operations are:

- Minimizing the number of transmitted beams.
- Reducing the repetition rate.
- Reducing the pulse length.
- Reducing the transmitted power.

The Parasound P70 is a hydroacoustic system for imagining sub-bottom structures up to 200 m below the sediment top layer. It radiates a beam of sound from a transducer installed in the ship bottom downwards towards the sea floor. The Parasound P70 installed on the RV *Polarstern* applies two primary high frequencies with high power and short duration: a signal at 18 kHz and a second tone from 20.5-23.5 kHz. The amplitude and frequency remain consistent over all transmitted pulses. There is a resulting low-frequency signal that is approximately 40 dB quieter than the primary signal and is created in the far field approximately 10 m below the transducer.

The mitigation options for the Parasound P70 are similar to those available for the Hydrosweep and are:

- Reducing the source level.
- Reducing the repetition rate.
- Reducing the pulse length.

All of these modifications have the potential to influence data quality by reducing the penetration depth of secondary signals, affecting the resolution, and affecting the quality of backscattered signals.

The Posidonia 6000 is an Ultra Short Baseline positioning and remote-control system for underwater equipment. It consists of a ship-mounted array with a receiving antenna and a transducer, which communicates with underwater beacons via hydro-acoustic signals. The antenna broadcasts a specific chirp signal which is then recognized by the beacon, and upon receipt, the beacon sends a reply with a different chirp signal. This received signal can then be used to calculate the bearing and distance between the antenna and the beacon. Additionally, the acoustic chirps emitted by the antenna can function as an acoustic release signal so that the beacon triggers mooring lines to detach from their anchors by acoustic remote control.

The communication between components in the Posidonia 6000 system is made by chirp signals, which are frequently shifted tones from 14-18 kHz with a duration of between 10-90 ms. These are transmitted hemispherically so that signals can be received in any spatial alignment. Although these chirps are 40 dB lower than the directional sound sources like the Hydrosweep and Parasound described above, the Posidonia 6000 transmits in all directions, resulting in a larger area being ensonified. There is only one parameter that can be adjusted for Posidonia

6000 operations: the repetition rate. As a result, the only way to mitigate noise emitted by the Posidonia 6000 is to increase the interval between transmitted sequences.

The results of the numerical modelling for each noise source are presented in a graphical format, showing propagation loss or received levels over range and depth. In the case of the noise propagated by the research vessel RV *Polarstern*, received noise levels can be calculated by looking up the Monopole source level, identifying the corresponding full octave centre frequency, looking up the propagation loss for this frequency band and corresponding depth, reading the numerical propagation loss value for the position of the received, and calculating received level. Results for the propagation of seismic airgun, Hydrosweep DS3, Parasound P70 and Posidonia 6000 noise are also presented.

See Annex 1 (Section A) for more details.

2.2 Investigating distribution and abundance of Antarctic marine mammals

Authors: Williams, R., Neilsen, K., Lo, C. Reiss, S. & Mendez-Bye, A.

As anthropogenic activity continues to increase and pressure the world's oceans, understanding the distribution and abundance of marine mammal species is critical for developing proper mitigation measures against human impacts. The purpose of this review was to collect information on the spatial and temporal distribution of marine mammal species in the Antarctic, a region where research on marine mammals is limited and the potential for human impacts on both seasonally migrating and endemic marine mammal species is high. The literature review specifically focuses on knowledge gaps and provides recommendations for improving distribution and abundance estimates for Antarctic marine mammals going forwards.

The study conducted a bibliometric search for research describing the spatio-temporal distribution and abundance of marine mammal species south of 60° South. The authors restricted their literature review to primary literature published in English as well as data shared in IUCN assessments and on open-access databases such as OBIS-SEAMAP and PANGAEA. The literature review was carried out by querying Google Scholar with the search terms 'Antarctic marine mammal abundance', 'Antarctic marine mammal distribution', and 'Antarctic marine mammal spatiotemporal' during December 2020 – February 2021. The sightings data obtained during this search were used to create species specific distribution maps.

The bibliometric search yielded 143 papers (including 23 IUCN species assessments), of which 118 focused on marine mammal distribution and abundance south of 60° South. The authors then added a further 73 papers that did not initially appear in the keyword search by consulting the reference lists of the publications and 10 further papers based on the recommendation of experts. As a result, the total number of publications used for the analysis was 201.

The species covered by the publications are grouped into the following categories:

- Phocids (5): Ross seal (Ommatophoca rossii), leopard seal (Hydrurga leptonyx), Weddell seal (Leptonychotes weddellii), crabeater seal (Lobodon carcinophagus), Southern elephant seal (Mirounga leonine).
- Otariids (1): Antarctic fur seal (Arctocephalus gazella)
- Mysticetes (8): common minke whale (Balaenoptera acutorostrata), Antarctic minke whale (Balaenoptera bonaerensis), sei whale (Balaenoptera borealis), pygmy blue whale (Balaenoptera musculus brevicauda), Antarctic blue whale (Balaenoptera musculus intermedia), fin whale (Balaenoptera physalus), Southern right whale (Eubalaena australis), humpback whale (Megaptera novaeangliae).

- Odontocetes (12): Arnoux's beaked whale (Berardius arnuxii), Southern bottlenose whale (Hyperoodon planifrons), Gray's beaked whale (Mesoplodon grayi), strap-toothed whale (Mesoplodon layardii), Cuvier's beaked whale (Ziphius cavirostris), Gervais' beaked whale (Mesoplodon europaeus), long-finned pilot whale (Globicephala melas), hourglass dolphin (Lagenorhynchus cruciger), killer whale (all ecotypes; Orcinus orca), spectacled porpoise (Phocoena dioptrica), sperm whale (Physeter macrocephalus), common bottlenose dolphin (Tursiops truncatus).

It should be noted that the Gervais' beaked whale and the common bottlenose dolphin were both excluded from the final review as only one record was available for each of these species. In addition, not all publications distinguished between Antarctic, common and dwarf minke whales, or Antarctic and pygmy blue whales, so those species were grouped as minke whale and blue whale respectively. The majority of the literature also did not distinguish among beaked whale species. Publications in this review dated back to the 1960s, and the 2010-2019 period contained the most publications for pinnipeds, mysticetes and odontocetes.

The review highlighted that there is a lack of up-to-date abundance and distribution data for many Antarctic species. The majority of literature was concentrated around a select few species (minke whales, humpback whales and crabeater seals), and, in particular, research in recent years has focused on minke whales, humpback whales, killer whales and Antarctic fur seals. Many of the odontocetes were mentioned in 10 or fewer of the publications (Arnoux's beaked whale, Gray's beaked whale, Cuvier's beaked whale, the strap-toothed whale, spectacled porpoise, long-finned pilot whale, and the southern right whale). The greatest number of publications available were related to mysticetes, followed by pinnipeds, and then odontocetes. Furthermore, the most widely available information tended to be related to the largest whale species, all species that were previously heavily exploited by whaling (however, some large whale species such as the sei whale were still data deficient).

There are various challenges and factors that help to explain why there is relatively little data available for the spatio-temporal distribution and abundance of marine mammals south of 60° South. As described in the review, these include:

- The remoteness of species' preferred habitat. For example, for any species that prefer dense pack ice such as the Ross seal, studies using helicopters, drones and satellite imagery are required instead of traditional vessel or land-based visual surveys.
- The cryptic nature of some species. The behaviour and detectability of Antarctic marine mammal species influence estimates of their abundance.
- The logistics and resources required for Antarctic population-level studies.
- The limits of species' ranges. For example, the lack of data on hourglass dolphin, long-finned pilot whale, southern right whale, and spectacled porpoise could be because 60° South represents the southernmost portion of their range.

After synthesising the available research on the spatio-temporal distribution and abundance of each Antarctic marine mammal species, a series of recommendations on how the currently existing knowledge gaps can be addressed is provided. These include conducting surveys during the spring, autumn and winter in addition to the summer months when survey effort is currently concentrated. The authors also recommend adding more survey effort to less-frequented parts of the Antarctic, such as the regions around Bellinghausen, Amundsen, and the Ross Seas.

See Annex 2 (Section B) for more details.

2.3 Behavioural responses of Antarctic marine mammals to anthropogenic noise: A review of relevant literature to facilitate noise threshold determinations

Authors: Nowacek, D. P., Friedlaender, A. S., Janik, V. M. & Southall, B. L.

Anthropogenic activity in the Southern Ocean, including Antarctic coastal waters, is likely to increase in the coming decades and, thus, has the potential to disturb marine mammals inhabiting these areas by generating acoustic energy (noise) into the marine environment. While often having negative connotations, the term ‘noise’ is used to describe acoustic energy within this study, as it is unlikely to have any beneficial effects for these animals. The following anthropogenic sources of noise are considered: vessels, seismic airguns, and hydroacoustic research equipment. The species of interest considered are those listed in Erbe et al. (2019a) and included in Table C. 1 of Annex 3 (species list and functional hearing group – not available in the text).

The objective of this study is to provide information to inform an EE process that will determine noise thresholds for behavioural responses of the species of interest (Table C. 1 of Annex 3). To provide the necessary information to guide the EE process, the following are presented:

- An overview of behavioural response studies (both controlled exposure experiments and observational efforts) and their results related to marine mammals and noise sources considered in this study based on relevant literature;
- A list of potential factors that may influence and explain the responses of Antarctic species to noise exposure; and
- A proposed severity scale to rank observed behavioural responses of the species of interest to various types of noise emitted by the noise sources considered in this study.

A list of the behavioural response studies reviewed in this study are presented in the Literature List (Annex 3, Supplemental Information A, B and C) and are organised by sound type. Studies were selected based on which were considered to be the most useful for the EE process and that had enough information to be scored with either the full or reduced severity scale protocols set out by Southall et al. (2021). There are some limitations as behavioural response studies do not exist for all species of interest for exposed to the three noise sources. Where no studies exist, the literature was reviewed for species as closely related as possible. However, there is a paucity of comparable literature as all pinniped species and one cetacean species occur only in Antarctica and many pinniped species do not have relatives outside of the Antarctic region.

When contemplating the potential for impact of some anthropogenic sounds, the sensitivity of individual species with respect to the sounds themselves must be considered, e.g. frequency spectrum, received levels, as the animal must be capable of perceiving the sound in order to exhibit a behavioural response. Behavioural response cannot always be assumed to occur and may be investigated under different experimental conditions. For marine mammals, there are wide ranges of hearing sensitivities and Southall et al. (2019) have provided the latest and most comprehensive review of these, in addition to the functional hearing groups for the species listed in Erbe et al. (2019a). Understanding hearing capabilities of individual species (including weighting functions) is important as they can then be compared with the characteristics (e.g., level, frequency range, impulsivity) of the anthropogenic noise sources included in this study and provide an informed estimate of the animal’s ability to detect and perceive sound.

Two primary experimental designs are used to assess the response of marine mammals to noise: controlled exposure experiments (CEEs) and observational studies. CEEs are sometimes referred to as 'playback studies' and consist of discrete exposure events where the researchers are in control of the timing (e.g., exposing whales at the surface vs. on a dive), the signal (e.g., short frequency sweeps mimicking a multi-beam signal), and the amplitude of the source noise. By controlling the source, researchers may collect baseline or 'before' data, so as to have control data against which to compare the 'exposed' or 'during' period. Additionally, they may utilize biologging devices to increase the range of data available when they determine if and how the animals respond. Thus, CEEs confer experimental advantages in terms of the amount and type of data which can be collected, in addition to the ability to conduct experimental controls. However, a limitation is that the sample sizes can be small relative to other experimental models. Observational studies are those where researchers make opportunistic observations upon the exposure of animal(s) to a noise source and generally result in larger samples sizes and longer sampling windows, and thus the potential to sample more contexts. However, this sound source is not controlled by the researchers as it is in CEEs and is dependent on opportunistic exposures so detailed exposure data cannot usually be obtained and experimental controls cannot be provided. In addition, the larger sample sizes come at the expense of details about the exposure and the animal's response.

A broad range of behavioural response studies were reviewed within this study and assessed using the assessment tools described by Southall et al. (2021). Southall et al. (2007) developed an initial response severity scale with which to review existing behavioural response literature for different sound types and marine mammal taxa and summarise the results. However, their results failed to agree upon a single 'threshold' for all responses or to suggest clear linear relationships in response severity scaled to the received noise level. Some species consistently showed sensitivity to noise levels (harbour porpoise) while others appeared more tolerant (humpback whales), and some individual species showed context-specific differences in responses. Despite these differences, it did provide a foundation from which assessments of response severity could be based. Southall et al. (2021) have provided new and adapted exposure matrices and a severity scale which have been adapted and applied in this study. These new assessment tools require a substantial amount of information about the exposure events and so studies were divided into those for which full severity scoring was possible, and those for which only reduced severity scoring was possible.

Full severity scoring was possible for a subset of studies (Annex 3, Supplemental Information A, B and C) , including whether any response was observed and if so, the score for the response. The new and updated exposure matrices and severity scale provided by Southall et al. (2021) is different from the 2007 version, as it considers behavioural responses in the context of important life functions: survival, feeding, and reproduction. For each of these categories, an ordinal score (0-9) was assigned for specific behaviours (e.g. cessation of vocal behaviour) to assist in assessing the severity of responses, with a score of '9' indicating the most severe responses such as stranding.

For the 'reduced severity scored' studies where it was not possible to glean the key details of exposure (e.g. individual animal exposure) or context, it was noted that it would be most beneficial for the EE process to provide a complimentary, albeit reduced, set of information and review of the studies themselves in the form of a short narrative. These narratives are provided in Annex 3 and include the following information:

- Type of methods used (e.g., experimental, historical data, modelling);

- Type of effects reported, both short term (e.g., behavioural changes, loss of acoustic space, click/buzz detection rates, social sound rates) and long term (e.g., health, distribution, reproductive/survival rates);
- Type(s) of exposure (e.g. seismic, vessel, echosounder);
- Estimated exposure levels (e.g. range(s) of possible SPLSs/SELs [measured or modelled] based on distances between animals and sources); and
- Lessons learnt.

It is acknowledged that a continuum of strategies exists for managing exposure to anthropogenic noise by using noise thresholds for behavioural responses of individual species. The US strategy protects individuals by dictating levels to which individual animals can be exposed, but it could be argued that this is not best for animals at the population conservation level, given the complexity of responses and influence of contexts. However, protecting vulnerable or particularly sensitive life history stages and/or species (e.g. mother-calf pairs, harbour porpoise) has value.

In contrast, the EU strategy protects populations by adopting measures to reduce noise overall to reduce exposure to a large number of animals, which can be considered better for conserving populations. However, this strategy fails to consider particularly vulnerable groups or species and their exposure to isolated or transient noise events that may result in significant impacts. There are both benefits and challenges when trying to balance individual protection with population level consequences when anthropogenic ocean noise is produced.

It is noted that there are nuances and complexity within behavioural responses to anthropogenic noise, and deterministic, single value thresholds for broad taxa do not really exist. The responses of animals are probabilistic in nature, vary by taxonomic groups and can be heavily influenced by contextual factors such as species, age/sex class, individual behavioural states, and interacting biological and contextual factors. In addition, many of the existing studies within the literature do not report many of the quantities and contextual information which would be helpful for understanding the context and severity of any responses observed. In many cases, the information is not available or was not collected, but in some cases the information simply was not reported. Thus, the authors advocate for a rational framework with which to assess available science and yield a manageable number of probabilistic response functions with which to make informed decisions systematically and objectively.

See Annex 3 (Section C and D for more details).

2.4 Antarctic marine mammals and the issue of noise-induced threshold shift

Author: Houser, D.

The marine mammals of the Antarctic Ocean have been studied and surveyed primarily during the austral summer. Advancements in the field of passive acoustic monitoring have improved the detection of vocalising animals, thus allowing the estimation of their abundance during seasons of dense ice coverage. This technology has also been used to monitor the increasing levels of underwater noise caused by human exploration. Noise sources associated with such anthropogenic activities in the Antarctic Ocean include vessels, seismic airguns, and bathymetric profilers. These sound sources pose a threat to the marine mammals of this region due to their ability to cause hearing loss and potentially affect the fitness of individuals and populations exposed to underwater noise.

The Protocol on Environmental Protection to the Antarctic Treaty went into effect in 1998 and dictates that environmental impact assessments must be conducted prior to any anthropogenic activities. The aim of this treaty is to protect the flora and fauna of Antarctica, although there is currently no unified approach to assessing noise impacts to marine mammals. Instead, member countries must establish criteria and exposure thresholds to regulate ocean noise. Additionally, there is a lack of consensus on the legal and regulatory definition of injury, which is further complicated by the complex mechanism of hearing loss and the variations in frequency-specific hearing sensitivity across marine mammal species.

Noise-induced hearing loss (NIHL) occurs when an animal's ability to perceive sounds is reduced due to an increased hearing threshold following fatiguing noise exposures. This shift in hearing sensitivity is considered temporary (temporary threshold shift or TTS) when the hearing threshold returns to pre-exposure levels over time, and permanent (permanent threshold shift or PTS) when hearing does not fully recover, and the same sounds need to exceed an elevated hearing threshold to be perceived by the affected animal. The mechanisms of TTS and PTS are not entirely mutually exclusive, and the hearing threshold shift can transition from temporary to permanent if animals are exposed to intense sounds that exceed the tolerance levels of the inner ear structures. The rate of hearing recovery is also influenced by the intensity, frequency content, and duration of an acoustic exposure. It has been observed that recovery can occur during the quiet periods between signals that are produced repetitively, although full recovery may be prevented if animals become exposed to new fatiguing noises before their hearing recovers from past exposures.

Hearing loss has typically been measured and studied in marine mammals by performing experiments with captive individuals and measuring their hearing sensitivity before and after controlled exposures. The primary means of assessing the ability of subjects to perceive sounds have either been behavioural (e.g. pressing a paddle or producing vocalisations after hearing a signal) or required measuring small voltages from the brain, which are produced in response to hearing a sound (method called auditory evoked potential). Caution is advised when comparing the results of studies using different methods for measuring hearing due to the differences observed in the magnitude of the hearing threshold shifts and the level of integration of the animal's response during the data collection process.

There is a limited number of species that have been studied in captivity and these include toothed whales such as the bottlenose dolphin (*Tursiops truncatus*) and harbour porpoise (*Phocoena phocoena*) or pinnipeds such as the harbour seal (*Phoca vitulina*). In contrast, there is little to no information available for large cetaceans like sperm whales and baleen whales, where most data have been informed by the anatomy of their inner ears and the frequency range of their vocalisations. Additionally, none of the Antarctic species have been involved in hearing loss studies; therefore, surrogate species are required to predict the risk of hearing damage until empirical data become available. The best suited surrogate species for predicting TTS in Antarctic species must have similar auditory system anatomy and sound production and hearing characteristics, as well as share a close phylogenetic relationship and have TTS data available from controlled studies (see Annex 4 for recommended surrogate species).

Hearing loss is of particular concern if it is sufficient to affect some aspect of the animal's ability to survive, acquire resources, or reproduce. Such instances may occur when the frequencies affected by noise-induced hearing loss overlap with the frequency ranges of signals used for communication, thus limiting the acoustic space of conspecifics, and reducing their reproductive success or foraging (either by reducing the likelihood of hearing echoes while echolocating or sounds associated with prey presence). Additionally, hearing loss within the range of frequencies used by predators may prevent animals from avoiding them, and, therefore, further limit their likelihood of survival. The true risk is dependent on how wide the frequency range of the hearing loss is and the characteristics of the sound source.

The risks associated with noise-induced hearing loss have led to the development of multiple mitigation frameworks and damage risk criteria, which have considered the audiometric data available for the marine mammal species studied to date, the magnitude of hearing loss observed during controlled studies, and the animals' reaction time following exposures to stimuli. Southall et al. (2007; 2019) proposed marine mammal auditory weighting functions for the prediction of noise-induced hearing loss, which emphasize the frequencies where animals are sensitive and de-emphasize the frequencies where they do not hear well. The provision of multiple functions is meant to accommodate the distinct hearing ranges and frequency-specific sensitivities of species groups such as baleen whales (low-frequency specialists) and porpoises (high-frequency specialists) and allows a certain degree of transferability to species with similar hearing and vocal production characteristics for which TTS data are not available. Furthermore, distinct criteria have been proposed for exposures to steady-state and impulsive sounds due to the differences in hearing loss magnitude observed following exposures to these distinct types of signals. Additional factors that could be considered by future studies and frameworks when predicting hearing loss include the synergistic interaction between steady-state and impulsive stimuli, the changes in level of impulsiveness of signals as they travel further away from the source, and self-mitigation of noise exposure observed in odontocetes during exposures to repetitive sounds.

The impacts of underwater noise caused by human activities to the hearing ability of Antarctic marine mammals should be predicted using the best available science and ideally be related to fitness consequences at a population level. Due to the shared responsibility of all nations utilizing the Antarctic Ocean, exploration needs should be balanced with standardised mitigation measures that rely on up-to-date scientific approaches and appropriate conservation principles. The Southall et al. (2019) auditory weighting functions are currently recommended for predicting NIHL in Antarctic species via the use of surrogate species for which hearing loss data are available.

Further details on the effects of noise on the hearing of marine mammals as well as the methods and protocols used to study hearing loss in marine mammals are further described in the Annex 4 (Section D).

2.5 Marine mammal monitoring and operational measures for mitigating noise from geophysical surveys and vessels: a review with emphasis on Antarctic waters

Authors: Brown, A. M., Ryder, M. R., Sinclair, R. R. & Verfuss, U.K.

This study provides a high level review of operational measures and real-time monitoring for mitigating the effects of noise from geophysical surveys and vessels on marine mammals, with a specific focus on Antarctic waters. Through a review of key literature and targeted interviews with 12 people with relevant experience, information was compiled on the effectiveness of different approaches used for real-time marine mammal monitoring to mitigate noise impacts, practical challenges associated with their implementation, along with their key strengths and limitations, and circumstances in which they are considered suitable. The scope of the review was focused on operational monitoring and mitigation methods (i.e. once a sound source is in the field and ready for operation), and included visual monitoring, electro-optical imaging sensors (thermal infrared {IR} and other spectral camera systems), passive acoustic monitoring (PAM), and the use of separate unmanned platforms. Notes on soft start procedures are also provided, as is a brief consideration of operational noise reduction measures for vessel noise and geophysical survey sources.

Marine mammal monitoring for mitigation purposes is generally conducted to minimise the risk of injury due to noise emitted by a sound source to negligible. Detecting an animal in time to implement mitigation measures before it enters a mitigation zone is, therefore, important to consider, with a high detection probability being vital. Visual monitoring is standard for 'mitigation monitoring', which is typically complemented or replaced (during times of low visibility) by PAM and, if available/feasible, additionally with thermal IR. Each of these methods has distinct strengths and limitations, and the extent to which they will contribute to effective monitoring will vary according to the circumstances and objectives to which they are applied, including the target species, required detection range, and environmental conditions. For example, in good visibility and under ideal deployment conditions, the use of visual monitoring supplemented by a thermal IR or PAM system may increase detections across all species, with PAM facilitating the improved detection of long/deep-diving odontocetes in particular. Both PAM and thermal IR allow detections during hours of darkness, and can increase detections in moderate sea states. Thermal IR is shown to be effective for large baleen whales and PAM is considered stronger for most odontocetes. In periods of higher sea states, fog or precipitation, PAM offers a method of detecting vocalising animals where visual observations or thermal IR may be ineffective.

In Antarctic waters, weather conditions, including frequent moderate and high sea states, precipitation and extreme cold, present one of the biggest challenges to visual monitoring. Such conditions make detection of animals challenging and present logistical challenges in terms of the positioning (inside or outside) of observers, having a sufficient number of observers to be regularly rotated, and potential compromises among the ship's crew to accommodate the number of observers. In such circumstances, the addition of a thermal IR system with automated detection, which have been shown to work well in cold environments and are somewhat robust to higher sea states, can provide a valuable supplement to visual monitoring. It was also noted that fog and precipitation were common in Antarctic waters, highlighting the value of PAM as a low-visibility monitoring tool in such conditions.

Based on the current stage of development of these different methods, a combination of visual monitoring, vessel mounted thermal IR system and appropriate towed PAM is recommended as the most effective approach to optimise real-time mitigation monitoring for geophysical surveys. It is acknowledged that such a suite of monitoring tools requires considerable resources, including investment in equipment and multiple trained personnel, and that the level of monitoring and investment into equipment should be proportional to the resulting benefit, considering the expected noise impact of an activity being undertaken and the sensitivity of the area and species present. It is also recognised that, in some circumstances, the use of a towed PAM array may be ineffective due to excessive masking by vessel noise; in such cases, as far as is safe and practicable, alternative platforms for deploying the PAM array should be investigated.

Please see Annex 5 (Section E) for further details.

3 Behavioural response expert elicitation summary

As described above, it is well established in the literature that marine mammal species are susceptible to anthropogenic noise disturbances, with concern over behavioural responses at an individual level and over population level impacts.

Across different jurisdictions there are different approaches and thresholds used in the impact assessment process, particularly relating to behavioural responses. Examples include assessments from the US National Marine Fisheries Service (NMFS 1995, 2005), harbour porpoise specific thresholds for the North Sea (Tougaard et al. 2015) and a variety of thresholds utilised in U.K. assessments (Sinclair et al. 2021). However, most of the noise thresholds developed thus far have been for species that do not regularly inhabit Antarctic waters. As a result, the transferability of these thresholds for use in noise impact assessments in Antarctica has not been deemed appropriate. To address these issues, this study focuses on a case study of activities permitted under German jurisdiction in Antarctic waters.

The German Environment Agency (UBA) has been designated as the competent authority under the Act Implementing the Environmental Protocol. As a result, Antarctic activities which are organised in Germany or proceeding from its territory must obtain an official permit from UBA. The scarcity of agreed noise thresholds has created difficulties in evaluating impact assessments for Antarctic activities in both a standardised and comparable manner. Therefore, there was a clear need for specific noise thresholds due to both the data deficiencies surrounding Antarctic marine mammal species, and the novel nature of the sound sources to these species.

To address this, this study presents the results of an EE workshop conducted to develop behavioural response thresholds for Antarctic marine mammal species for three key noise stressors inclusive of research seismic activity, vessel noise (specifically that of the RV *Polarstern*) and noise emitted from hydroacoustic research equipment (inclusive of Posidonia 6000, Parasound P70 and Hydrosweep).

An EE is a well-established technique for use in data-deficient situations in which there is a pressing management or conservation need (Runge et al. 2011, Martin et al. 2012). The EE techniques can be implemented to both translate and combine information obtained from a group of experts with ranging backgrounds and expertise, into quantitative statements. A critical component of this technique is that the elicitation must be designed and facilitated in a manner that ensures that biases, such as social dominance, anchoring and others are minimised (Morgan 2014). The expert elicitation approach utilised in this study followed the concepts outlined in the Sheffield Elicitation Framework (SHELF) (Astfalck et al. 2018, Gosling 2018).

A panel of experts were invited to participate in the process, with varying backgrounds in behavioural response studies for a range of marine mammal species. Pre-workshop webinars were hosted with the invited experts, and short studies (in both report and presentation formats) were provided to the experts to assist with summarising the information on the noise sources, Antarctic marine mammal species abundances and distributions, and a review of the current state of knowledge of behavioural responses of marine mammals to anthropogenic noise. For the purpose of the elicitation, the experts elicited under a pre-defined and agreed definition of 'molest' or significant disturbance. This was defined by UBA as '*all actions and activities that either have an impact on individual fitness, a physiological impact or result in disruption to or interference with an organism's behavioural pattern or life processes, or that have a negative impact on the psychological well-being of the animal*'. In this context, 'molesting' is not necessarily consisting of physical contact with the animal.

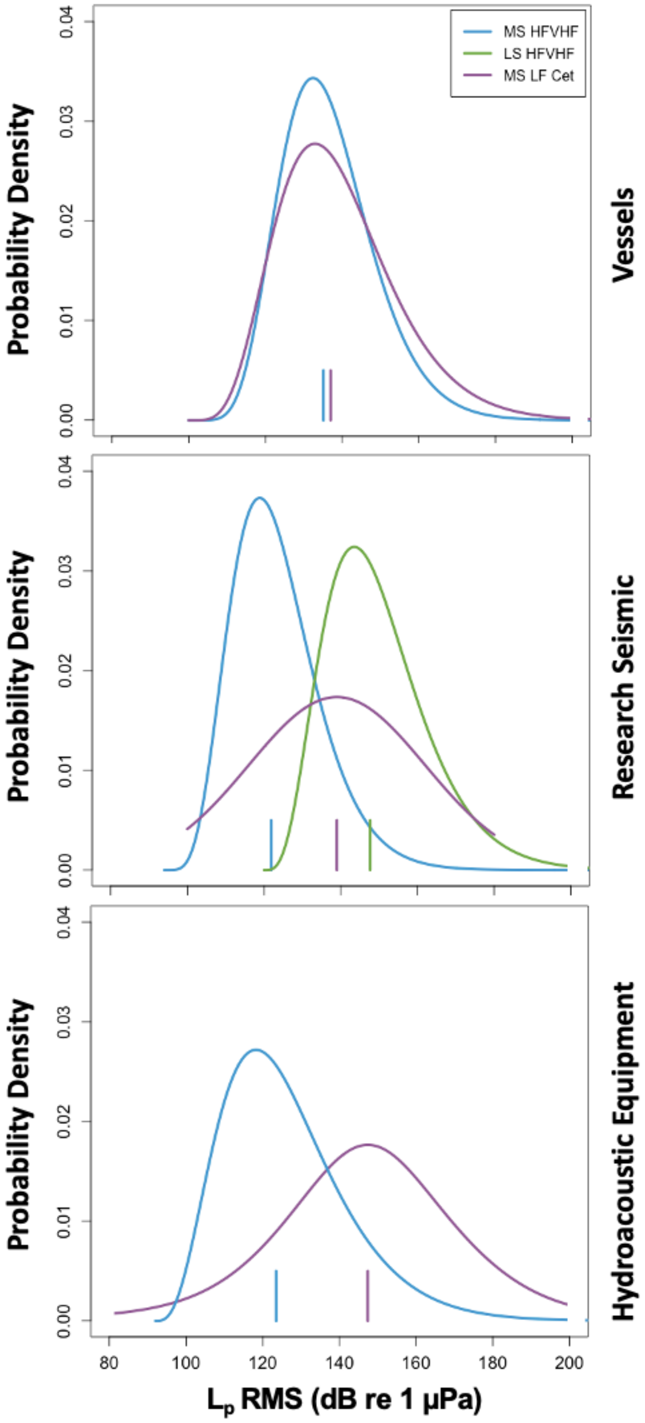
Vessel noise and seismic airguns were elicited separately for each marine mammal grouping (Table 1) as,. while both emit broad-frequency sound, one source emits continuous sound while the other emits pulsed sound, which might elicit behavioural reactions at different received sound levels. Different types of hydroacoustic equipment (Hydrosweep, Parasound P70, and Posidonia 6000), were elicited together. This was justified by the similarities in the central frequencies of Hydrosweep (12-17 kHz), Parasound P70 (18-22 kHz), and Posidonia 6000 (10-14 kHz). Marine mammal species were grouped according to their hearing groups as proposed by Southall et al. (2019, Table 1). The elicitation generated a series of noise thresholds for the most sensitive species of each Antarctic marine mammal species group and captured the current scientific uncertainty (represented by the spread in the distribution around the median). For each elicited distribution (Figure 1), the median provides the 'best estimate' and, therefore, the threshold to be used (see Chapter 5). These values represent the received level at which a significant response was predicted to occur in the average animal of the most sensitive species group (severity score 4+; sensu Southall et al. 2021). The spread of the distribution represents the marked scientific uncertainty around the received level at which the average animal in species groups responds but not the variation between individuals. Specifically, this means that the distributions presented here cannot be used to estimate the probability or likelihood that animals respond to a noise source. This work is fully described in Darias O'Hara et al., (in review).

Table 1: Antarctic marine mammal species, their grouping into hearing groups according to Southall et al. (2019), and species groups allocated to noise thresholds for behavioural response ("molest"). Noise thresholds for injury follow the grouping of the Southall et al. (2019) hearing groups: LF – low frequency, HF – high frequency, VHF – very high frequency, PCW – phocid carnivores in water, OCW - other marine carnivores in water.

Species	Southall et al. (2019) hearing group	Species group behavioural response thresholds
Hourglass dolphin (*Lagenorhynchus cruciger*) Spectacled porpoise (*Phocoena dioptrica*)	VHF cetaceans	HF/VHF cetaceans
Southern bottlenose whale (*Hyperoodon planifrons*) Arnoux's beaked whale (*Berardius arnuxii*) Gray's beaked whale (*Mesoplodon grayi*) Cuvier's beaked whale (*Ziphius cavirostris*) Gervais' beaked whale (*Mesoplodon europaeus*) Strap-toothed whale (*Mesoplodon layardii*) Long-finned pilot whale (*Globicephala melas*) Killer whale (*Orcinus orca*) Sperm whale (*Physeter macrocephalus*) Bottlenose dolphin (*Tursiops truncatus*)	HF cetaceans	HF/VHF cetaceans
Common minke whale (*Balaenoptera acutorostrata*) Antarctic minke whale (*Balaenoptera bonaerensis*) Sei whale (*Balaenoptera borealis*) Pygmy blue whale (*Balaenoptera musculus brevicauda*) Antarctic blue whale (*Balaenoptera musculus intermedia*) Fin whale (*Balaenoptera physalus*) Southern right whale (*Eubalaena australis*) Humpback whale (*Megaptera novaeangliae*)	LF cetaceans	LF cetacean
Ross seal (*Ommatophoca rossii*) Leopard seal (*Hydrurga leptonyx*) Weddell seal (*Leptonychotes weddellii*)	PCW	Seals

Species	Southall et al. (2019) hearing group	Species group behavioural response thresholds
Crabeater seal (*Lobodon carcinophaga*) Southern elephant seal (*Mirounga leonina*)		
Antarctic fur seal (*Arctocephalus gazella*)	OCW	Seals

Figure 1: **The final subjective probability distributions of the defined behavioural response noise thresholds (for the average animal of the most sensitive species in each group (unless denoted)) in response to noise from vessels (top), research seismic (middle), and hydroacoustic equipment (bottom). LF – low frequency, HF – high frequency, VHF – very high frequency, MS – most sensitive species in group, LS – least sensitive species in group.**



Source: Author’s own.

4 Injury expert elicitation summary

To enable a standardised assessment of the impact of anthropogenic noise on the auditory systems of marine mammals, Southall et al 2017 and 2019 reviewed existing literature and developed noise thresholds for temporary and permanent reductions in hearing sensitivity. As the risk of auditory system impact depends in part on the hearing range of an animal, they grouped species with similar presumed hearing abilities into different species groups. A major consideration for the recommended criteria was based on the estimated onset of temporary hearing loss following exposure to noise. Reductions in hearing sensitivity induced by sound exposure can recover over time. Hearing can either return to normal, pre-exposure hearing sensitivity (temporary threshold shift, TTS), or some amount of hearing loss can remain permanently (permanent threshold shift, PTS).

In many countries with environmental frameworks for regulating anthropogenic noise, the estimated onset of PTS is used to determine the risk of injury from anthropogenic noise to marine mammals. In Germany, TTS is used as a measure for injury, as damage to hearing is regarded as injury within the meaning of paragraph 44(1) of the Federal Nature Conservation Act, and this damage can be temporary or permanent (ASCOBANS 2014). Experimental studies with laboratory animals suggest that not all noise exposures that generate TTS leads to tissue damage, though the amount of TTS that causes an animal's health to be impaired is unknown. Low levels of TTS in marine mammals (measured minutes after exposure) have been shown to recover within minutes or hours of the cessation of noise (Finneran 2015, Houser 2021). While a temporary reduction in an animal's hearing due to noise exposure may not lead to permanent tissue damage or loss of sensory ability, repeated exposure to TTS can lead to PTS (Lonsbury-Martin et al. 1987).

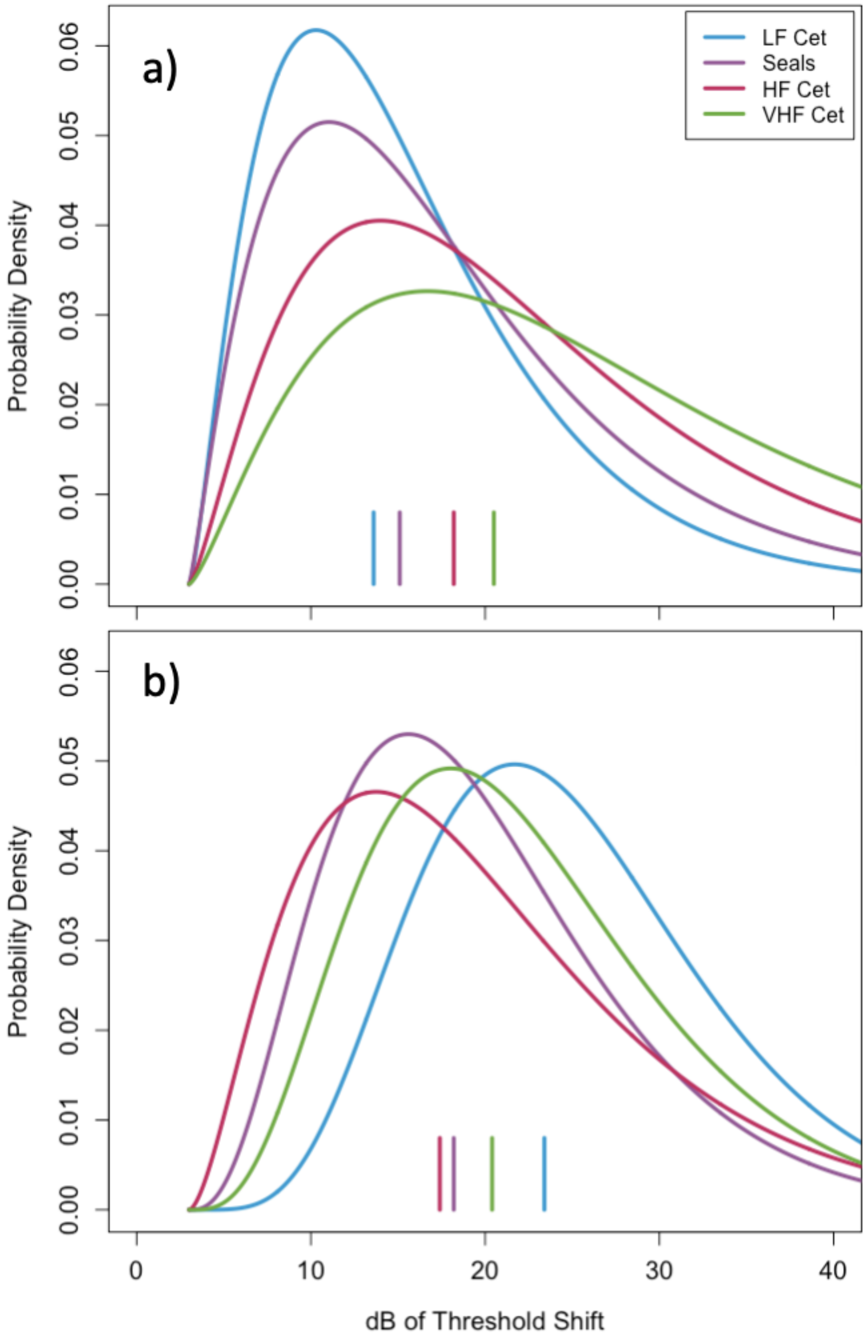
Here, we used EE techniques to estimate the amount of threshold shift (TS) that potentially causes injury in individuals of different marine mammal species groupings. UBA defines injury as '*significant (=non-negligible) damage to the physical integrity or health of each individual animal such as a temporary/reversible impairment*'. UBA considers TTS as a temporary/reversible impairment. Noise stressors considered in the elicitation comprised:

- Vessels, used for both research and tourism purposes, with focus on Germany's RV *Polarstern*;
- Seismic airguns used from shipboard platforms for research purposes; and
- Hydroacoustic equipment operated from shipboard platforms including Hydrosweep, Parasound P70, and Posidonia 6000 active acoustic sources.

For the elicitation of the magnitude of TS causing injury, marine mammal species were collated and grouped in relation to the hearing groups established by Southall et al. (2019, Table 1), including very-high-frequency (VHF) cetaceans, high-frequency (HF) cetaceans, low-frequency (LF) cetaceans, phocids in water (PCW) and other carnivores in water (OCW).

Within the constraints of the elicitation, a diverse group of marine mammal experts estimated when the probability of a TS would significantly and negatively affect biological and/or life history functions of a marine mammal. We used a structured EE process to judge the relationship between the magnitude of threshold shift and when injury might occur in Antarctic marine mammal species groups exposed to vessel noise, and noise produced by research-related seismic and hydroacoustic equipment. The elicited distributions from the expert elicitation are shown below (Figure 2). The distributions represent the current scientific uncertainty and the vertical lines indicate the median (see Chapter 5). This work is fully described in Verfuss et al., (in review).

Figure 2: **The final probability distributions of the threshold shifts (a temporary reduction in hearing sensitivity) within an average animal of a species group caused by (a) vessel/seismic noise and (b) hydroacoustic equipment that is considered as injury. Legend shows colours for low frequency (LF), high frequency (HF) and very high frequency (VHF) cetaceans and seals (as classified in this document).**



Source: Author’s own.

The process highlighted high uncertainty in how a TS affects individual marine mammals. This uncertainty was driven by a lack of data, especially for baleen whales, but also by varying views of the experts on when recoverable hearing loss becomes significantly damaging to an animal. While most experts considered the loss of acoustic space to orient, socialise and forage to be the limiting factor to when a TS becomes significant and to limit an animal's ability to function within normal biological limits, some also considered that anatomical changes to the auditory system significantly impact an animal. At the other extreme, some experts considered TTS to be relatively benign to animals, with significant effects expected only as TS approached levels closer to PTS onset.

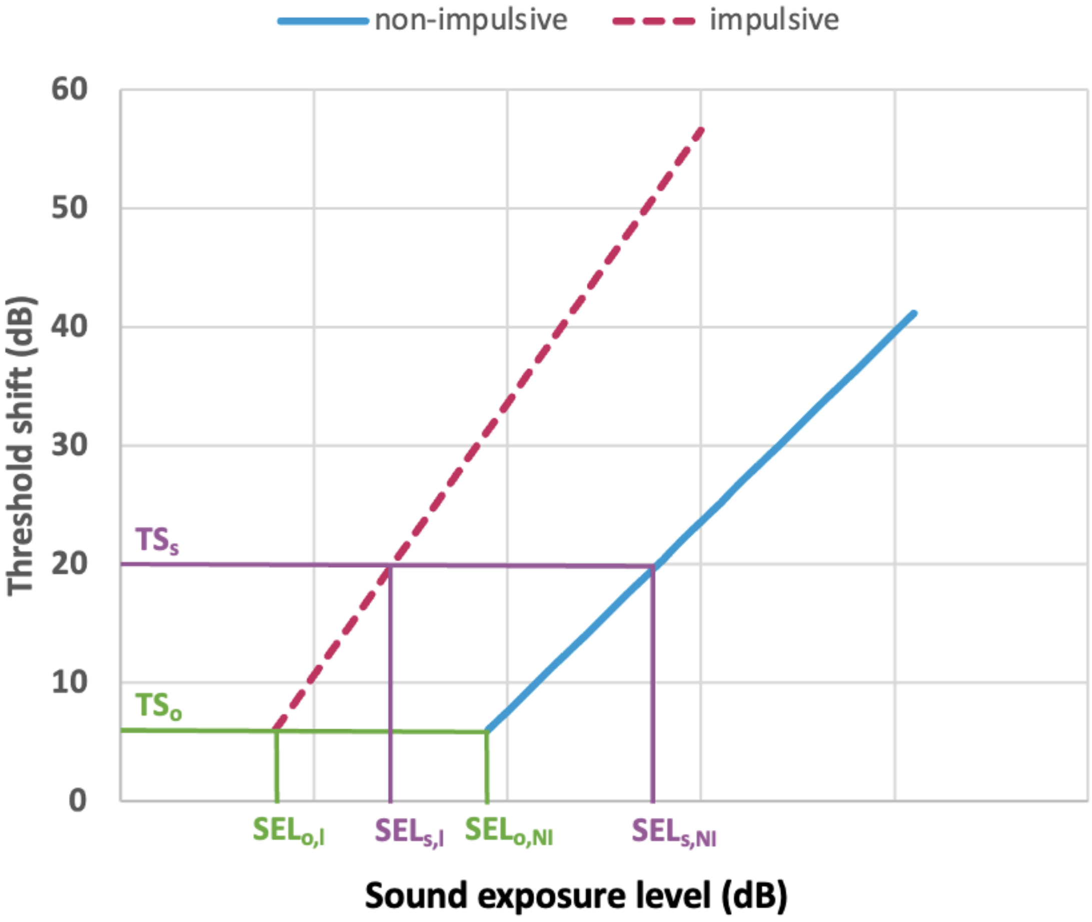
Due to the uncertainties surrounding when TS results in injury, most, if not all, experts were conservative with their estimates during the elicitation process. As in the behavioural response elicitation, the median resulting from this EE represents the 'best estimate' of the true value of the quantity of interest (sensu Gosling 2018), and the spread in the distribution around the median captures the prevailing scientific uncertainty. The scientific uncertainty around the best estimate (the spread of the distribution) expresses the uncertainty of when TS becomes significantly damaging for an average animal. It does not represent the variation between individuals and can, therefore, not be used to draw conclusions for animals with a sensitivity below or above average.

In order to derive absolute threshold values based on the median TS thresholds, the method of Southall et al. (2019) can be used. While knowledge of noise induced hearing effects in marine mammals has increased greatly since 1994, further research, discussions and agreements are needed to improve noise impact assessments and reduce uncertainties.

The purpose of these noise thresholds is to inform the impact assessment process for regulatory bodies with responsibility for Antarctic waters, such as UBA, but may be applicable more widely by other regulatory bodies for the impact assessment process in Antarctic waters. This elicitation generated specific thresholds for specific scenarios (and with assumptions clearly stated) for each species group and noise stressor (from which the required species stressor threshold can be derived). In this EE, the median represents the 'best estimate' of the true value of the quantity of interest (Gosling 2018). Therefore, these values represent the noise thresholds to be used in the application outlined in the study (i.e. the median of the distributions presented for each noise stressor and marine mammal grouping). However, the process clearly highlights the uncertainty around these parameters.

The EE approach provided a formal mechanism to provide scientific advice based on limited available data, on quantities of interest to regulators. This study provided the starting point for addressing key issues in the impact assessment process, through the derivation of single threshold distributions across three noise stressors in Antarctic waters, for all marine mammal species found within this region. This allowed the provision of scientific advice for a pressing management issue through quantifying the experts' uncertainty around the evidence, partly arising from substantial data gaps. Going forward, it was recommended that more data on the specific noise stressors in Antarctica and species response to it will significantly improve the knowledge base and help improve uncertainty.

Figure 3: **Illustration of how to calculate absolute noise thresholds (here shown as sound exposure level (SEL)) for a significant threshold shift (TS_S) (purple) based on the methodology used by Southall et al. (2019), using the sound exposure level (SEL0) at the onset of temporary threshold shift (TTS) (TS_0 = 6 dB) (green) and the growth rate for impulsive (red dashed line, growth rate of 2.3 dB threshold shift per dB SEL) and non-impulsive sound (blue line, growth rate of 1.6 dB threshold shift per dB SEL). This example is based on an exemplary significant threshold shift (TSs) of 20 dB, resulting in the noise threshold (SELs) for impulsive (I) and non-impulsive (NI) sound. Note that this value is exemplary only and depends on the species group and noise source.**



Source: Author’s own.

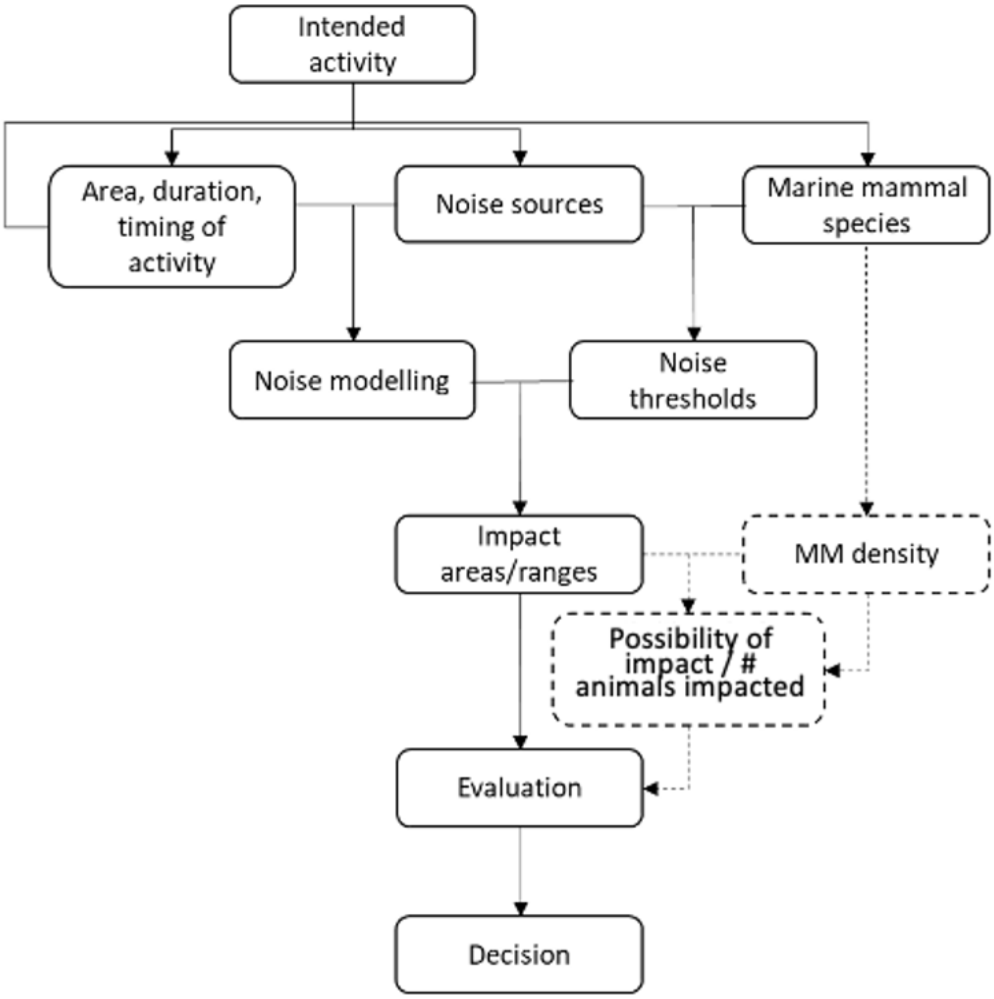
5 Guidance

This chapter provides summary guidance on what to consider when evaluating the environmental impact of anthropogenic noise within the EIA or IEE and proposes a set of noise thresholds to be used in order to determine impact ranges around Antarctic noise sources. These noise thresholds will help to quantify the impacts of a significant behavioural response (“molest”) by or injury to an individual of a marine mammal species.

For assessing the noise impact on Antarctic marine mammals of an intended activity (according to the requirements of the EP and AIEP), we propose to follow the steps shown in Figure 4 and described in further detail in a separate internal report to UBA. It covers the following and provides recommendations of how decisions by the competent authority can be robustly made under the EP.

- Source activity specific information
  - Area and timing (duration, repetition, season, time of day) of activity,
  - Noise sources operated in the activity area and characterisation of their noise emission,
  - Marine mammal species that may occur in the area during the time of activity and associated information,
- Conduct noise modelling specific to the activity area and the noise emission of the noise sources,
- Select noise thresholds specific to the marine mammal species and noise sources,
- Compute impact areas and/or ranges by applying the noise thresholds to the noise modelling output, considering the duration of the activity,
- Calculate the possibility of a marine mammal being molested or injured, and/or the number of animals potentially being exposed to the possible risk of molesting or injury, in cases where marine mammal density in the activity area is known or can be estimated,
- Evaluate the magnitude of the potential impact of the activity based on the results of the assessment, and
- Use the evaluation to decide on the permit application.

Figure 4: **Flow chart of steps and information needed in the environmental impact assessment process to reach a decision on an intended activity. See text for further explanations. Dotted lines indicate obligatory pathways to support the evaluation and decision. MM – marine mammal.**



Source: Author's own.

5.1 Noise thresholds

The noise thresholds for assessing impact ranges or areas of significant behavioural response ("molest", Table 2) and injury (Table 3) in Antarctic marine mammal species are provided for the three noise source classes discussed above. These thresholds are based on probability distributions of behavioural response thresholds (Darias O'Hara et al., in review) and magnitudes of auditory threshold shifts causing injury (Verfuss et al., in review) elicited in the expert workshops of the project. These thresholds are specifically for Antarctic species and the noise sources considered in the elicitations.

Table 2: **Noise thresholds for significant behavioural response based on the best estimate of the probability distributions as shown in Figure 2. LF – low frequency, HF – high frequency, VHF – very high frequency, MS – most sensitive species in group, LS – least sensitive species in group.**

Noise stressor	Species group	Threshold L_p (dB re 1 µPa)
Vessel	LF cetaceans, seals	137
Vessel	HF/VHF cetaceans	135
Seismic airgun	LF cetaceans, seals	139
Seismic airgun	HF/VHF cetaceans	MS: 122, LS: 147
Hydroacoustic equipment	LF cetaceans, seals	145
Hydroacoustic equipment	HF/VHF cetaceans	123

Table 3: **Magnitude of threshold shift (TS) causing injury (as defined above) in an average animal of Antarctic marine mammal species and corresponding noise thresholds for injury based on the best estimate of the probability distributions as shown in Figure 2. Noise thresholds are based on a hearing group weighted $L_{E,p,w}$ cumulated over the duration of a noise exposure and/or over multiple repeated noise exposures occurring in sufficiently rapid succession as described by Southall et al. (2019). LF – low frequency, HF – high frequency, VHF – very high frequency, PCW – phocid carnivores in water, OCW – other marine carnivores in water.**

Noise stressor	Species group	TS causing injury (dB)	Injury thresholds based on weighted $L_{E,p,w}$ (dB re 1 µPa²s)
Vessel	LF cetaceans	13.6	184
	HF cetaceans	18.2	186
	VHF cetaceans	20.5	162
	PCW	15.1	187
	OCW	15.1	205
Seismic airgun	LF cetaceans	13.6	171
	HF cetaceans	18.2	175
	VHF cetaceans	20.5	146
	PCW	15.1	174
	OCW	15.1	192
Hydroacoustic equipment	LF cetaceans	23.4	176
	HF cetaceans	17.4	175
	VHF cetaceans	20.4	146
	PCW	18.2	175
	OCW	18.2	193

5.1.1 Background to decision making under the EP

Decision making is extremely challenging when assessing the context of the anthropogenic effects of noise on marine mammals. There are multiple elements that can feature in a decision framework depending on the needs of the regulator, the legislation under which decisions are made and which articles are the focus of the decision-making process.

Noise-emitting activities in the Antarctic have the potential of impacts on marine mammals (Article 4 paragraph 3 and Article 3 paragraph 4 of the AIEP). The key elements to consider in decision making are:

- The EP protects native birds and mammals at the individual level. According to these regulations, activities that molest, handle, capture, injure or kill a native mammal or bird are prohibited, except in accordance with a permit (Annex II, EP).
- The EP stipulates that any activity to be carried out in the Antarctic must be assessed in advance for its impacts on the Antarctic environment. Within this prior environmental impact assessment according to Article 8 of the EP in conjunction with its Annex I, the impacts on populations of native animals are to be considered.

Assessing individual level impacts is relatively straightforward. By following the flowchart in Figure 4 and using the thresholds developed here – it is possible to assess whether any marine mammal will be impacted. In such instances a special permit would be required for activities to proceed (we discuss how these individual level impacts might scale to the population level below). Where assessments are made considering impacts that affect the population, this is very challenging – due to the complexity of population dynamics and the limited data upon which to base decisions. A further limitation in the regulation of research activities in the Antarctic is the lack of a documented workflow to help practitioners to consider impact assessments and make decisions, both in consideration of the existing legislation but the broader context of populations at greatest risk.

Annex II of the EP states to “"take" or "taking" means to kill, injure, capture, handle or molest, a native mammal” (Article 1 (g)) and that “harmful interference” means among others “any activity that results in the significant adverse modification of habitats of any species or population of native mammal, bird, plant or invertebrate.” (Article 1 (h) (vi)). Article 3(1) Annex II of the EP indicates “taking or harmful interference shall be prohibited, except in accordance with a permit“, and shall be issued only in the circumstances pursuant to Article 3(2) Annex II of the EP. Article 3(3) (b) Annex II of the EP indicates that permits shall be issued in a limited fashion such that, if animals were killed by an activity, that “only small numbers of native mammals or birds are killed and in no case more native mammals or birds are killed from local populations than can, in combination with other permitted takings, normally be replaced by natural reproduction in the following season".

Therefore, considering how the number of animals predicted to be impacted by an activity in the context of the number of animals that would be replaced by natural reproduction in the following season might provide a reasonable foundation for decisions in Antarctic waters.

A number of population approaches exist to aid decision makers. The range from rule-based approaches such as Potential Biological Removal (PBR) through to predictive modelling approaches (e.g. those developed using the Population Consequences of Disturbance (PCoD) framework) (see Sparling et al 2020 for a review of methods). For Antarctic species, however, data is so limited that detailed population modelling is not possible in the majority of cases currently. Rule-based approaches such as PBR represent widely-used methods to help assess whether or not predicted levels of anthropogenically derived mortality will affect a population reaching or exceeding a specific target population size. Practically the tool allows users to estimate the number of individuals that might be 'safely' taken from a population whilst still allowing the population to maintain or achieve the level targeted by a regulator. As highlighted above, this is in line with the Article 3 of Annex II of the EP – with the goal of ensuring no more animals are taken from the population than could be replaced by natural reproduction in the following season.

PBR is relatively simple to calculate, only requiring one recent or current population estimate and it does not require the user to make decisions about what is an acceptable level of population change – this decision is intrinsic to the PBR calculations. However, it is important to state that there are a number of disadvantages to such an approach – and such an approach must be carefully considered.

6 Conference summary

Following the conclusion of the core elements of the project, a final conference was convened to summarise progress and promote dissemination of the outputs of the project. This conference was held in Berlin, Germany at the Schmiede on EUREF Campus, on March 14th and 15th 2023.

6.1 Proceedings

6.1.1 Opening session & background to the project

The opening session provided a brief overview of the aims and objectives of the project. This was followed by an address from the regulatory body point of view, detailing the impact assessment process and the regulatory need for noise thresholds.

6.1.2 Anthropogenic underwater noise sources commonly used for research in Antarctica

This session detailed the noise characteristics of anthropogenic noise sources utilised for research in Antarctica. This included detailed information on the noise characteristics of seismic airguns, hydroacoustic research equipment and vessel noise, specifically that of the RV *Polarstern*, the vessel commonly used for these surveys.

Contributions were made by the participants during this session, raising questions on the positioning systems of the RV *Polarstern* and how these contribute to the cavitation noise created by the propellors. Further questions were raised and clarified on the methodology behind the measurements taken for this study and the inferences related to surface reflection when calculating sound propagation.

6.1.3 Distribution and abundance of Antarctic marine mammals

This session examined the distributions and abundance of Antarctic marine mammals. This session focused solely on Antarctic marine mammal species and highlighted the IUCN and population status of these species (if known), as well as the current understanding of species distributions in the region.

Contributions were made by the participants during this session which largely focused on discussing potential data gaps in the study in which certain observer data from ship surveys appeared to have not been included, as the study utilised solely peer-reviewed and certain grey literature sources. These points were addressed by the speakers and further actions were created for the relevant participants to provide the data sources they felt were missing from the study, and for the authors of the study to assess these and determine if these new data would be appropriate to include in an updated version of the study.

A further discussion point aimed to address how these data could be utilised in the impact assessment process. The session concluded that the use of density surface models in more recent years has expanded the methodologies for the assessment of species which have data limitations. With priorities placed on baleen whales and beaked whales and evaluate whether there is sufficient data to inform density surface models and potentially allow for extrapolation beyond the range of observations.

6.1.4 Behavioural responses of Antarctic marine mammals to Anthropogenic Noise

This session reviewed the current state of knowledge on behavioural responses of Antarctic marine mammals to anthropogenic noise, specifically focusing on the three noise sources in this project (Seismic airguns, vessel noise and hydroacoustic research equipment). During the session, key data gaps were identified including that there is no hearing data for baleen whale species, which added complications to the assessment of behavioural responses as it was unclear to what extent these species could hear the noises emitted in their environment.

The discussions during this session surrounded the novelty of the noise stressors in Antarctic waters examined in this study and how this would impact the behavioural responses of species in the region. It is considered that Antarctic marine mammals would be more naïve to these noise stressors in comparison to individuals generally located in areas of higher industrial activity, and therefore it is assumed that these animals would show stronger behavioural responses to these stressors. However, a point raised during this discussion was that although Antarctic waters may have less anthropogenic noise, there are other unique natural noises found in polar regions (e.g., ice breaking). Suggestions included collecting data on the ambient noise levels in these environments, and to further increase our understanding on the hearing capabilities of baleen whale species.

6.1.5 Antarctic marine mammals and the issue of noise-induced threshold shift

This session presented on the implications of noise stressors on the hearing of marine mammal species. This presentation provided background on the physiology of the mammalian ear and the implications noise-induced threshold shift on marine mammal species.

The main discussion points included the implications of temporary threshold shift (TTS) and the impact this has on the communication space of marine mammal species due to the masking effects of TTS. A further point was related to baleen whale hearing weighting functions, and how these were calculated since there are currently no audiograms available for baleen whale species. It was confirmed that these are developed through extrapolating from other hearing groups and assumptions made from the anatomy of the ear.

6.1.6 The expert elicitation process

This session focused on the methodology of expert elicitation and how this technique is used within the scientific field. Topics presented during this session included background on the applications of expert elicitation, and detailed information on the methodology itself including how it is designed to mitigate bias, the protocols used and summarised the limitations and benefits of such approaches.

Discussions focused on the selection of experts and how to avoid personal bias towards a topic. This was addressed through the justification that experts are selected from a wide range of backgrounds and expertise, with the participating experts undergoing both training before the elicitation to attempt to avoid any potential biases as much as possible, and through the monitoring of discussions and expert behaviour by the facilitator of the elicitation.

A further point raised was that the information provided to experts relating to the background literature (in the ‘evidence dossier’) could possibly influence and bias the experts in their decision making as some results may not be published in the literature. This was clarified that the experts are asked before the workshops to provide papers that they feel relevant, and that experts who participated in the elicitations are very experienced in their respective fields and as such, the literature provided to them is likely to not be new information (i.e., such experts are already familiar with most relevant literature in the field).

6.1.7 Behavioural response expert elicitation results

This session focused on presenting the results from the expert elicitation which elicited noise thresholds for a behavioural response of Antarctic marine mammals to the three noise stressors in this project. The presentation concentrated on the expert selection and the scoping of this elicitation, the data gaps surrounding the topics of behavioural responses of marine mammals to anthropogenic noise and the elicited noise thresholds.

The majority of the discussions centred on the justification for utilising the median of the distributions presented as the noise threshold. It was suggested that it would be useful to quantify the uncertainty. This was clarified that this would not be appropriate due to the risk of misinterpretation by future readers that any other values other than the median could be utilised for impact assessments, which is not the intention of this elicitation. It was further explained that the uncertainty surrounding these elicited noise thresholds is already reflected in the distributions presented.

A further point was raised that the elicitation focused on the most sensitive species of a given hearing group, and in doing so the elicitations were potentially biased by the literature available as studies only tend to publish results in which a behavioural response was found, not in instances where the hypothesis that an animal would respond to a given stressor, is disproven. This was discussed and clarified that the evidence dossier contained multiple examples in which no visible response was observed. It was also reiterated that the level of stressor included a stress response, and this might not be represented by observers whilst the animal is at the surface.

6.1.8 Auditory injury expert elicitation results

This session focused on the results of the expert elicitation on auditory injury in Antarctic marine mammals in relation to the three noise stressors focused on in this project. The presentation included the background to the elicitation, the scenarios in which the experts elicited on, and the elicited noise thresholds and associated distributions for each noise stressor.

The discussions were focused on the four-minute recovery time for marine mammals in relation to their hearing and exposure to anthropogenic noise sources, and the potential risk of having experts participating in both expert elicitation workshops (auditory injury and behavioural response). These were clarified, with the justification for a four-minute recovery time through the physiology of marine mammal hearing and giving clarity on how expert bias was accounted for, explaining that the experts which participated in both workshops had very broad views and would not have brought complications to the elicitation process.

6.1.9 Guidelines for utilising noise thresholds

This session focused on a guidance report which aims to provide guidance to the regulatory body (UBA) on how to utilise the elicited noise thresholds for behavioural response and auditory injury in the impact assessment process. This presentation provided background to the project, specifically current thresholds and the impact assessment process, and opened for discussion on how the thresholds can be best used.

In the discussions, it was suggested that for the auditory injury noise threshold, additional information should be added on the associated recovery times for these thresholds. It was further clarified that this would not be appropriate due to the broad range of recovery times which are both frequency and species dependent. It was also discussed and confirmed that during the auditory injury elicitation, experts considered both the physical integrity, and the vital rates of the marine mammal species which resulted in the definition becoming difficult to disentangle for the experts, ultimately creating more conservative noise thresholds.

A final discussion point was raised on the inclusion of uncertainty in a numerical format in the form of a standard deviation for each of the thresholds. This was further clarified that this would not be appropriate due to the risk of misinterpretation by readers, and that the uncertainty is already reflected in the probability distribution figures.

6.1.10 Round table discussion: Results and guidance

This session was conducted in the form of a round table discussion, and aimed to discuss the expert elicitation workshop results for both behavioural response and auditory injury, and the guidance document.

Discussions initially centred on the most appropriate methods to present the uncertainty surrounding the noise thresholds elicited for both behavioural response and auditory injury. The justifications for not reporting a numerical value for uncertainty were clarified, and it was agreed that the best way forward to improve the elicited thresholds, is to reduce the uncertainty through improved research efforts in dedicated areas of research priority for Antarctic marine mammals.

An issue was raised on the terminology used in the auditory injury elicitation, which must be clarified and used in a uniform manner. Specifically, the term significant damage is also referred to as significant impact. One definition should be selected and used consistently throughout. This was confirmed that this would be adjusted. It was also agreed that the definition provided to the experts for the purposes of the elicitation was provided by UBA, and as such these thresholds can only be used in the context of which they were elicited. These are not transferable.

A short presentation on current EU noise regulation approach and how they are utilised and calculated, was provided. This encouraged discussions which focused on the political aspects of the decision making, which regions are responsible for developing these thresholds, the implementation cycle of these thresholds and what scientific evidence is utilised to develop them. It was clarified in this discussion that the approach taken in the expert elicitations differs from the EU regulation approach. The elicited thresholds considered population levels and individuals as key drivers, not habitats. It was agreed that due to the data deficiencies surrounding Antarctic marine mammals, a habitat-based approach, would not be appropriate.

Finally, an example was provided on the approach taken by UBA when conducting impact assessments, to provide clarity on how the noise thresholds elicited in this project would be utilised by regulators. This was followed by discussions on how best to mitigate for impacts, through calculating impact distances and hotspots in which animal densities would be higher than in other areas within the study site.

6.1.11 Round table discussion: The way forward

The session aimed to discuss and agree the appropriate next steps following this project, with emphasis on research priorities.

An important topic in discussing the next steps following this project was how to more accurately estimate the impact of anthropogenic noise stressors on Antarctic marine mammals, with behavioural response being a key driver in this discussion. A clear need was more studies to improve the knowledge base underpinning updated thresholds in the future. It was agreed that an essential component for assessing estimating impact, both for behavioural response and auditory injury, is the details of the modelling that is carried out (i.e., the assumptions of the exposure).

Discussions were had on mitigation, specifically new developments of mitigation protocols. It was agreed early on that it would be sensible to organise a separate mitigation workshop for this. It was further agreed that the aspects that need to be considered are dominated by specific research into mitigation, but also supported by research into Antarctic marine mammal behavioural responses to the noise stressors they are exposed to. Some concerns were raised that additional mitigation measures may impact the research that is ongoing in Antarctica, specifically impacting ship time of the expedition, consideration should be given to the additional resources needed to conduct this.

It was also suggested that based on the sound propagation modelling, distances should also be attached to the threshold values and considered. Species dependency would also be a key aspect of this if a precautionary principle was to be utilised to its full extent. Due to the data deficiencies surrounding Antarctic marine mammals and their specific distributions and densities, regulators would have to consider the most sensitive species which is likely to be amongst the most data deficient and as such, the densities estimated would be a minimum number. It was clarified that UBA is already taking a similar approach and acknowledged that whilst we have sparse knowledge on the species present in the area, there are now, due to this project, better and more precise thresholds to assist the impact assessment process.

Further to this discussion, there was agreement that exemptions should be given by UBA for high priority research activities. Protocols were suggested including increasing passive acoustic monitoring in real time. It was further discussed that current mitigation measures including visual aids, satellite imagery and radar are not promising in terms of close-range mitigation. It was suggested that decreasing the source level to the least amount of energy being input into the water as possible, was a viable solution to reduce risk of impact.

Concerns were raised on permanent threshold shift (PTS) occurring for low-frequency cetaceans if they are considered in an exemption, as the currently modelling suggests that PTS would occur in clusters, even if the animals are sparsely distributed. It was further added that the seismic survey activity in Antarctic waters already utilised minimal seismic energy, and that further decreasing this would not be possible due to the geophysical nature of the environment. Specifically, the continental shelves increase the soundscape due to reflectivity, and the thickness of the seafloor requires deeper penetration. This discussion was concluded through addressing the onset of PTS for low-frequency cetaceans in relation to seismic airgun activity, clarifying that we assume hearing thresholds for this hearing group, and are very precautionary in that aspect. Highlighting that obtaining hearing thresholds for low-frequency cetaceans is an important research priority.

The session concluded on with what the research priorities should be for Antarctic marine mammals. These research priorities included:

- Real-world measurements of the noise stressors in the Antarctic environment,
- Controlled exposure experiments,
- Studies which obtain more information on the animals’ use of the water column, through targeted tagging studies,
- The use of current data in a more effective and appropriate manner, utilising sources that are not currently considered,

- Improving methods for monitoring for mitigation,
- Dose response curves,
- Movement pattern models,
- Reduction of noise emitted through marine vibratory methods,
- Revised population estimates, and
- Site usage drivers and predictive modelling.

In concluding the session, it was commented that the proportion of animals impacted is the least priority on the list above, and that there are other pressing research needs that will need to happen to further improve the impact assessment process.

6.1.12 Concluding statements

The concluding statements of the Conference were delivered, thanking participants for their participation and contributions to discussions and reiterated the research priorities to the group. The remaining timeline of the project was presented, and the conference was brought to a close.

7 Conclusions and outlook

With concerns over the detrimental effects of underwayer noise, this project has developed the foundation of a noise protection concept for research activities in Antarctica. Principally, this project has developed new thresholds to support improved impact assessments. These noise thresholds help to quantify the impacts of a significant behavioural response ("molest") by or injury to an individual of a marine mammal species. To derive these new thresholds the project has had to consider each element of impact assessment, the empirical information and supporting knowledge available to inform new thresholds achieved via expert elicitation.

In addition to the noise thresholds, the larger assessment process (including mitigation) has been considered. This involved working through the legislative framework under which marine mammal populations in Antarctica are protected in mind, the current impact assessment and decision making processes, to map out future research needs. As a result a series of topic areas where future research can support further noise concept development are provided below.

Three key elements affecting the total number of animals being molested or injured (as defined here) are the underlying density estimates of animals around the source, the source characteristic and propagation of these sources and the thresholds at which animals are affected. This study has derived new thresholds with the best available information, but underlying density estimates and noise characteristics remain critical sensitivities affecting impact assessments. Therefore critical needs are:

- Improved abundance and density estimates (with estimates of uncertainty) for Antarctic species for times of year and regions most often impacted.
- Real-world measurements of the noise source characteristics and propagation of different sources in the Antarctica environment.
- Consideration of how noise emitted might be reduced to minimum levels required for research purposes (e.g. reduced source levels, only critical systems used on vessels).

Essential components of estimating impact, both for behavioural response ('molest') and injury as defined here, are the assumptions around the exposure of animals. In classic noise impact assessment approaches, the key factors in the model are distribution and dive depth of the animals during exposure events. Three-dimensional models which considers both horizontal and vertical movements can be too cumbersome to model. But a simplified model which only considers the vertical movement of an animal in a fixed position, can provide an appropriate solution to generate more precise impacts of a given anthropogenic activity. To continue to improve noise thresholds or noise impact assessment approaches (e.g. considering the probabilistic nature of response and the exposure of the animals), the following areas should be advanced.

- Controlled exposure experiments for priority Antarctic species, to help better parameterise thresholds for behavioural response to noise stressors in the Antarctic environment. In the long term, such studies can provide sufficient data to inform noise thresholds, including dose-response thresholds (if considered appropriate within the legislative framework). In the short term, new empirical information can support improved decision making for updating fixed noise thresholds.
- Continuing experimental studies to improve knowledge about the hearing and threshold shift (and consequences of shifts) in Antarctic species (or their surrogates) will be invaluable to support improved thresholds in the future.

- Better knowledge on the horizontal and vertical movement patterns of Antarctic species to improve mapping of the occurrence and temporal and spatial overlap with activities which can be cross-reference with key periods for Antarctic species. This can inform movement models to improve estimates of exposure.
- Development of population consequences frameworks for the most important populations. Note: such frameworks require significant information to construct – but can provide a roadmap for evidence gaps and data needs.
- Finally, improved methods for monitoring of Antarctic species and the live mitigation of impacts to support the execution of research activities in a sustainable manner is advised. However any mitigation approaches must be proportionate and ideally not hinder the research activity.

A Annex 1 – Review of anthropogenic noise sources commonly used for research in Antarctica

Authors: Schuster, M. & Erbe, C.

A.1 Anthropogenic underwater noise sources in the Antarctic

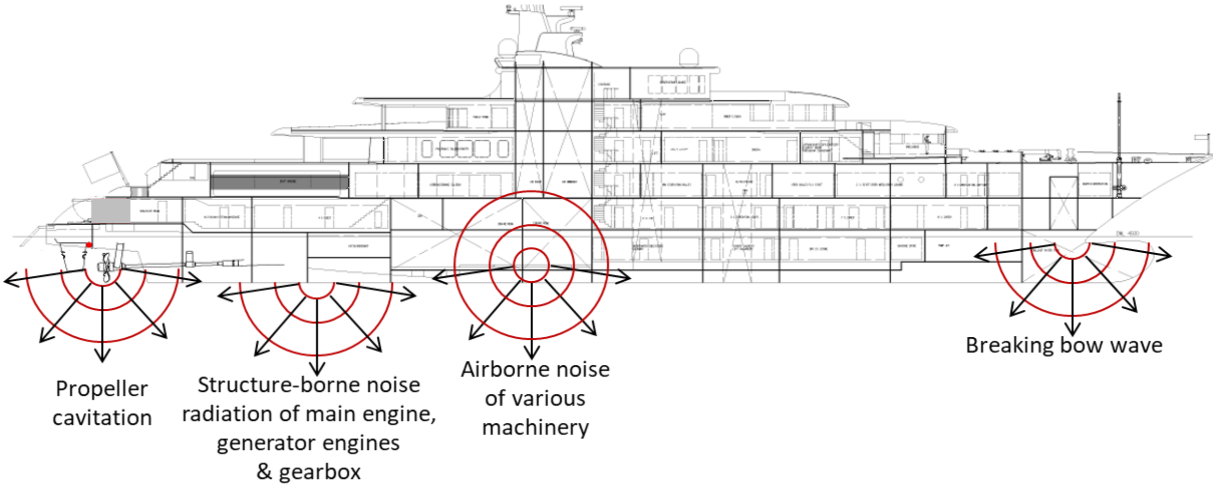
A.1.1 Ship noise

Background information

This section focuses on the noise produced by the ships that are used for research in Antarctic waters today and on those that are expected to operate in Antarctic waters in the future. Many research activities in Antarctica require ship operation for a vast range of purposes. These ships radiate noise into the environment by numerous noise sources of machinery and propulsion on board, where most ships radiate continuous noise in a broad frequency range from 10 Hz up to more than 100 kHz (e.g. documented in Wisniewska & Teilmann (2018). Typically, the overall noise level is described by one source level spectrum which summarizes contributions of all noise contributors on board, as shown in Figure A. 1.

The most common vessel for German research activities is the icebreaker RV *Polarstern* which has been investigated for radiated noise during different operating conditions, see Kraus, et al. (2011). A key characteristic of the RV *Polarstern* is the high source level that is produced at 6 knots reduced speed (Figure A. 2). This occurs since the ship is driven by controllable pitch propellers which tend to cavitate heavily at reduced pitch. Even at zero speed during station keeping the ship is expected to be a dominant noise source because main engines are permanently running. It is expected that the intensity of radiated engine noise can be higher than of deployed hydroacoustic equipment. However, there is currently no data available to quantify RV *Polarstern's* radiated noise at zero speed.

Figure A. 1: Sketch of typical underwater noise sources on board of a ship.



Source: Author's own.

Sound characteristics

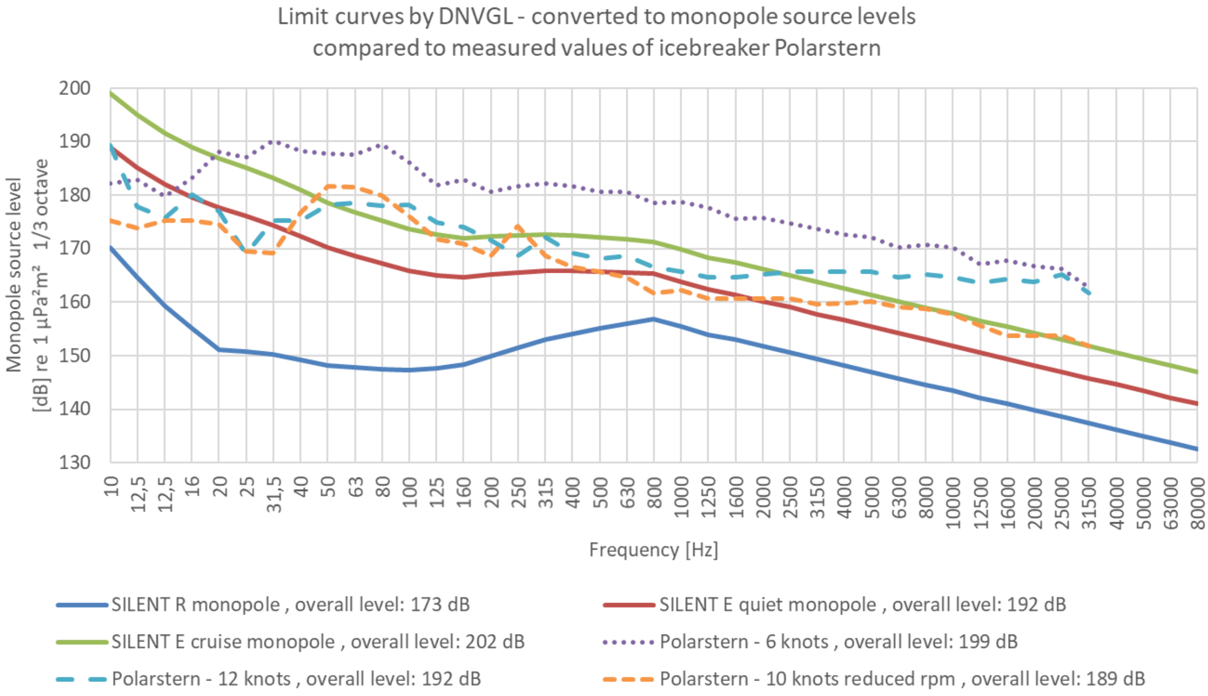
Ship noise can be considered as monopole (omnidirectional) for the purpose of modelling received levels with environment-specific sound propagation models that account for the surface reflections. The surface reflections appear for sound sources just below the sea surface and result in a vertical dipole radiation pattern. This needs to be considered if sophisticated sound propagation models are not available that account for the surface effect with resulting vertical directivity. Moreover, significant directivity in horizontal direction (forward, aft, starboard, port side) has been observed in specific frequency ranges, depending on operating conditions by Arveson & Vendittis (2000). In any case, a quantitative consideration of horizontal directivity requires extensive investigations. Consideration of measured values in broadside direction as omnidirectional source level is deemed a reasonable proxy in a context as considered here.

Two possibilities are presented here to generate input for propagation modelling of ship noise. The first option is applied for the current German research vessel (RV) *Polarstern* which has been investigated in detail with respect to underwater radiated noise Kraus, et al. (2011). The reported radiated noise levels from these measurements were converted to monopole source levels according to the procedure in Section A.3. As a second option, specifications of newly built ships are applied as an estimate. If underwater noise is relevant for a newbuild project, this is frequently defined in the building contracts based on underwater noise notations of classification societies, examples are found in Chmelnitsky & Marianne (2016). Among these, SILENT R is a typical design target for modern research vessels. SILENT E is proposed for design of cruise vessels which operate in noise-sensitive areas. SILENT E cruise describes the ship at design speed (typically around 20 knots), SILENT E quiet is valid for reduced speed up to 11 knots. As further discussed in Section A.3 these limits define the maximum source level for new built ships if defined in the building specification.

Examples of octave frequency source spectra of the different ship types introduced above are provided based on limit curves issued by classification societies. As an example, the values given by DNV GL (2017) are converted to monopole source levels. Further description of limit curves and their conversion to monopole source levels is found in Appendix . The ship types included are SILENT R monopole, SILENT E quiet Monopole, SILENT E cruise monopole, and the ship RV *Polarstern* at three speed categories (6 knots, 12 knots, and 10 knots with reduced shaft speed and controllable pitch propeller at full pitch). In the past years, an increasing number of new built research vessels (e.g. RSV Nuyina built for the Government of Australia) and cruise vessels (e.g. Celebrity Eclipse built for Celebrity Cruises) were accredited for compliance with DNV GL Silent Class requirements. In addition, some research vessels have undergone dedicated treatment of noise sources during major conversions to comply with underwater noise requirements of classification societies (e.g. *RV Aranda*, operating for the Government of Finland).

There is currently no publication available for radiated noise at zero speed. However, noise measurement data from acoustic moorings which were deployed in the vicinity of RV *Polarstern* at zero speed do exist (e.g. conducted by AWI) that could be analysed if relevant.

Figure A. 2: Monopole source levels of RV *Polarstern* in three operating conditions compared to three limit curves of modern ship classes. All radiated noise levels on which this graphic is based were converted to monopole source levels by numerical modelling.



Source: Author's own.

Technical mitigation

The mitigation of ship noise can be categorised into three groups:

Operational measures to reduce underwater noise contribution of the noisiest source on board (e.g. investigation of dependence between ship speed and radiated noise to adjust speed to "quiet steaming" while sailing in sensitive habitats). This requires knowledge of radiated noise levels.

Technical modifications of the existing vessel such as treatment of dominant noise source (engines, propellers) or installation of secondary measures to isolate noise sources from the surrounding water, e.g. by air injection into the water ("Prairie masker belts" as installed on some navy ships).

Dedicated noise control during the construction of new vessels (e.g. resilient mounting of engines, propeller design with focus on avoidance of cavitation).

As mentioned in point 1, mitigation of ship noise based on operation profiles requires knowledge of the dependency between operating condition and radiated noise, such as presented in Figure A. 2 for different operating conditions of the RV *Polarstern*. The use of an on-board noise monitoring system enables the crew to fine-tune noise emissions and to identify noisy off-designs conditions which were not investigated before.

A.1.2 Seismic airguns

Background information

Marine seismic airguns are impulsive sound sources, designed to generate low frequencies for the investigation of deep sub-bottom structures under the seabed. In most scientific applications, multiple airguns are towed behind a ship, at depths between 2 to 5 m. Devices are arranged in arrays to increase the signal's penetration depth into the sediment (Figure A. 3).

Figure A. 3: Sketch of Airgun array geometry (2 airguns), applied during Polarstern voyage "PS104" in Feb-ruary and March 2017 in Antarctica (dimensions not to scale).

Source: Author's own.

Each airgun consists of a chamber filled with compressed air (Figure A. 4), where a sudden release of the air into surrounding water generates a sharp, impulsive pressure wave which propagates through the environment. Frequency content and source level of this impulse are to be optimized with respect to geo-acoustic requirements. These relevant parameters can be simulated by numerical tools which yields the possibility to design specific array configurations with respect to minimization of source level. However, in practice it is likely that undesired additional high frequency noise is generated by mechanisms like rattling of valves and bubble cavitation. This high-frequency content can extend up to 100 kHz according to Goold & Coates (2006). It can only be reliably quantified by measurements of the full airgun array geometry, considering the towing depth, firing pressure and airguns specifications. A shallow towing depth below 10 m under the water surface results in a pronounced focusing of low frequency acoustic energy towards the bottom as the low frequency part of the signal is affected by Lloyd Mirror effect[1]. The shallower the towing depth, the more pronounced is the focusing of the acoustic energy.

Airgun arrays implemented by AWI in Antarctic waters are designed to be compact in order to reduce the risk of collision with ice. There are different types of airgun clusters available, those demonstrated in Figure A. 4. However, larger airguns of type Bolt PAR CT800 which were used in earlier projects were phased out[2] in the meanwhile, therefore the conducted modelling is based on configurations of 2 and 3 GI guns only.

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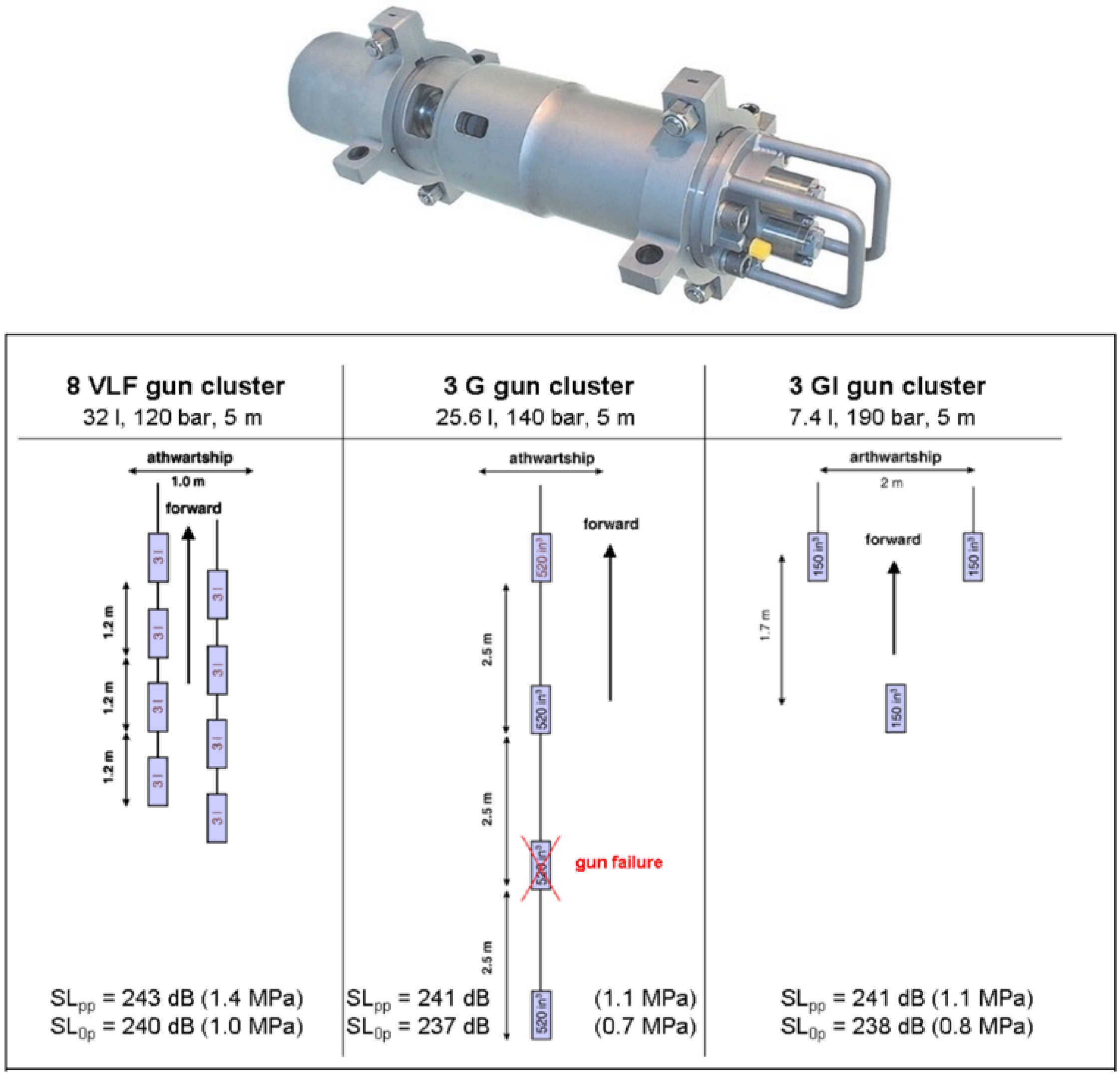
[1] The Lloyd mirror effect occurs for low frequency underwater sound sources in vicinity of the water surface. All sound pressure incident on the water surface is inverted by the pressure release boundary. The superposition of both waves leads to zero sound pressure in vicinity of the water surface. The frequency range of the Lloyd mirror effect depends on the source depth, receiver depth and horizontal distance of the measurement geometry. Figure A.27 illustrates the Lloyd mirror effect for a shallow source 5 m below the water surface measured at an angle of 30 ° off the horizontal direction. For this specific geometry, attenuation due to interference of direct path and surface path is seen approximately below 200 Hz.

[2] According to personal communication with Dr. Karsten Gohl (AWI), 20.04.2021.

Figure A. 4: Upper panel: GI (2.4 Litre) airgun by Alfred Wegener Institute (2018) . Lower panel: Alternative dimensions of larger airgun arrays, as used by AWI in earlier projects.

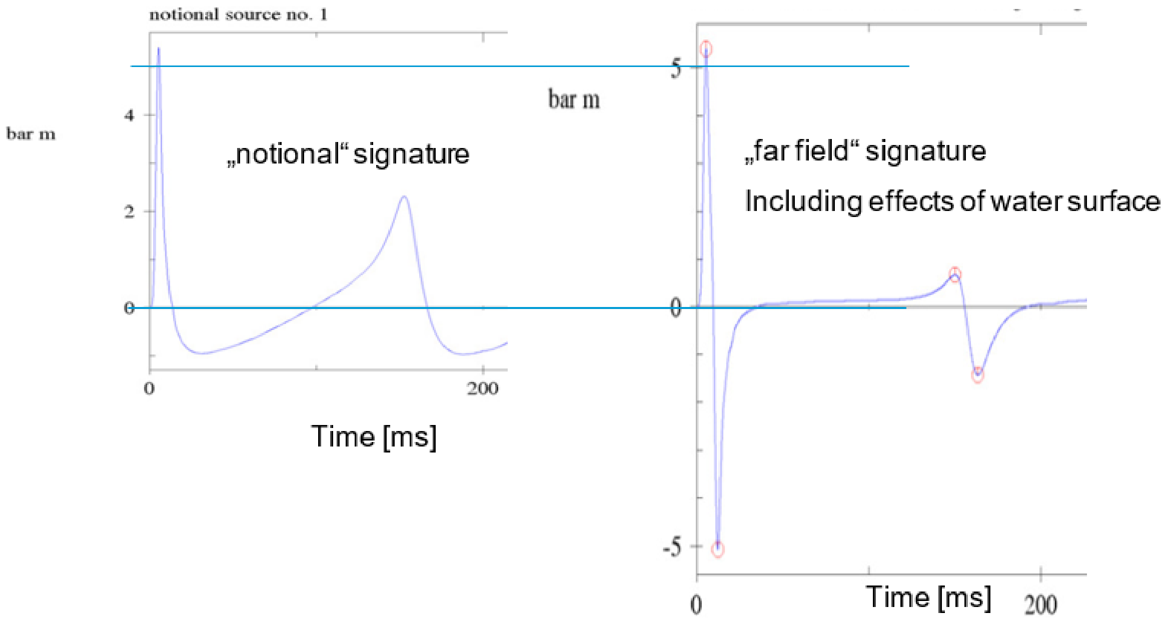


Source: Alfred Wegener Institute.

Sound characteristics

Far-field signatures of airguns are composed of the direct pressure pulse which is formed by interaction of the individual guns, and of the signal reflected at the surface. The latter is called "surface ghost" or "ghost". Due to phase shift at the boundary between water and air, the sharp positive pressure pulse is followed by a negative pulse at similar magnitude (Figure A. 5). Presence of the surface ghost involves that peak to peak pressure of the far field signal is higher than peak to peak pressure of the airgun pulse without surface interaction ("notional signature"). The overall energy of notional signature and far field signature are identical if reported for same distance. However, the peak to peak characteristics and frequency spectrum are dependent on the depression angle between source and receiver.

Figure A. 5: **Comparison of notional signature (left) and far field signature (right) of a single G gun at 140 bar firing pressure, computed by software NUCLEUS in Boebel et al. (2009).**



Source: Author’s own.

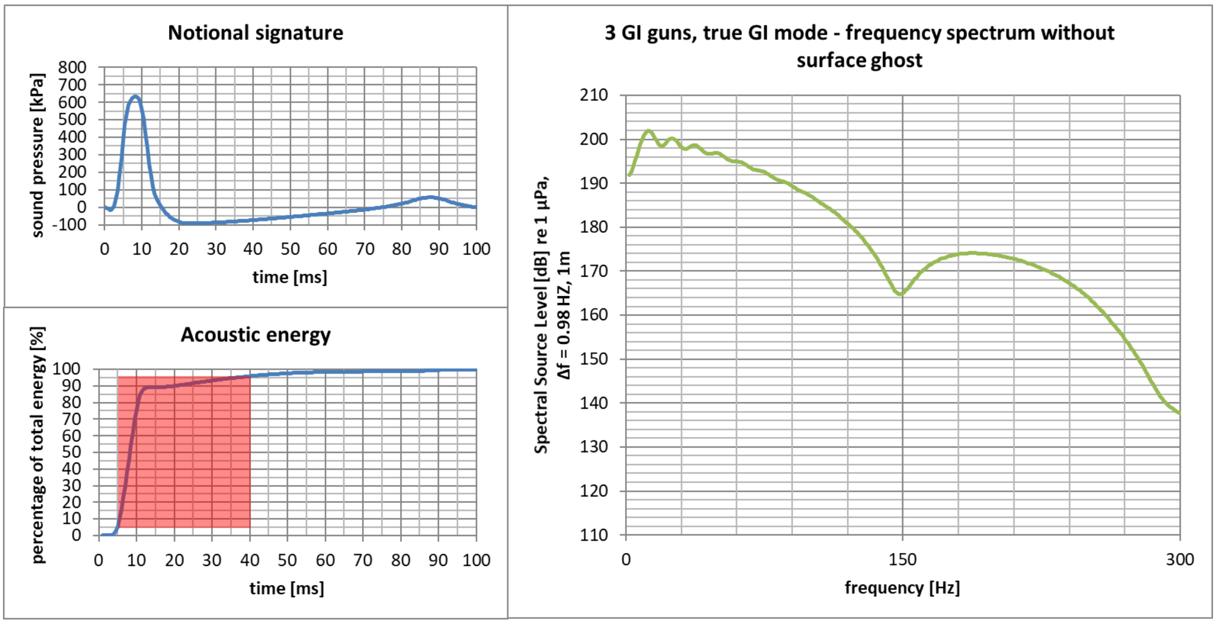
Since the airguns discussed here are typically deployed from the RV *Polarstern* at a speed of 5 knots, it is expected that the sound energy above 300 Hz is dominated by ship noise. All further reported numbers in Table A. 1 and modelled received single shot Sound Exposure Level (SEL) values in this pamphlet are based on notional source waveforms of numerical modelling in Boebel, et al. (2009).

Table A. 1: **Technical data of Airgun far field signatures in keel aspect (including contribution of surface ghost), computed by software NUCLEUS for 1 m distance, see Boebel et al. (2009). Values for “Single GI gun in true GI mode” are not available. The parameter “95% energy bandwidth” describes a frequency below which 95% of the acoustic energy are concentrated in the spectrum.**

Parameter	Cluster 3 GI guns, true GI mode	Parameter	Cluster 3 GI guns,
Zero-to-peak SPL (1m source level)	238 dB re 1 µPa²m²	224 dB re 1 µPa²m²	231 dB re 1 µPa²m²
Peak-to-peak SPL (1m source level)	241 dB re 1 µPa²m²	229 dB re 1 µPa²m²	236 dB re 1 µPa²m²
Single pulse SEL (1m source level)	211 dB re 1 µPa²s	202 dB re 1 µPa²s	210 dB re 1 µPa²s
95% energy bandwidth	193 Hz	173 Hz	105 Hz
Towing depth	Typical 5 m		
Firing pressure	190 bar		
Repetition rate	Typical 10 seconds		

Parameter	Cluster 3 GI guns, true GI mode	Parameter	Cluster 3 GI guns,
Total Air volume	10,2 l (~450 in³)	2.4 l (~150 in³)	10,2 l (~450 in³)

Figure A. 6: Waveform, energy and spectrum for notional source level signature in 1 m distance of a 3 GI gun cluster in true GI mode, low pass filtered at 256 Hz. The red box highlights a pulse length which contains 90% of the acoustic energy. The blue box indicates the 95% energy bandwidth in frequency domain. Please note that this signature is based on numerical modelling which yields good accuracy in the frequency range of useful seismic signals. The higher frequency range generated by gun mechanics and bubble cavitation is not contained in this figure.



Source: Author’s own.

Technical mitigation

Mitigation of radiated airgun noise can be structured in two aspects:

1. Optimization of the airgun array: Minimize source level by adjusting firing pressure and minimize sideward noise radiation (maximize downward directivity) by adjusting towing depth. All adjustments must consider the quality of seismic data and requirements for safety against collision with ice.
2. Maximize inter-pulse interval to reduce cumulative energy. This must consider the resolution of seismic data.

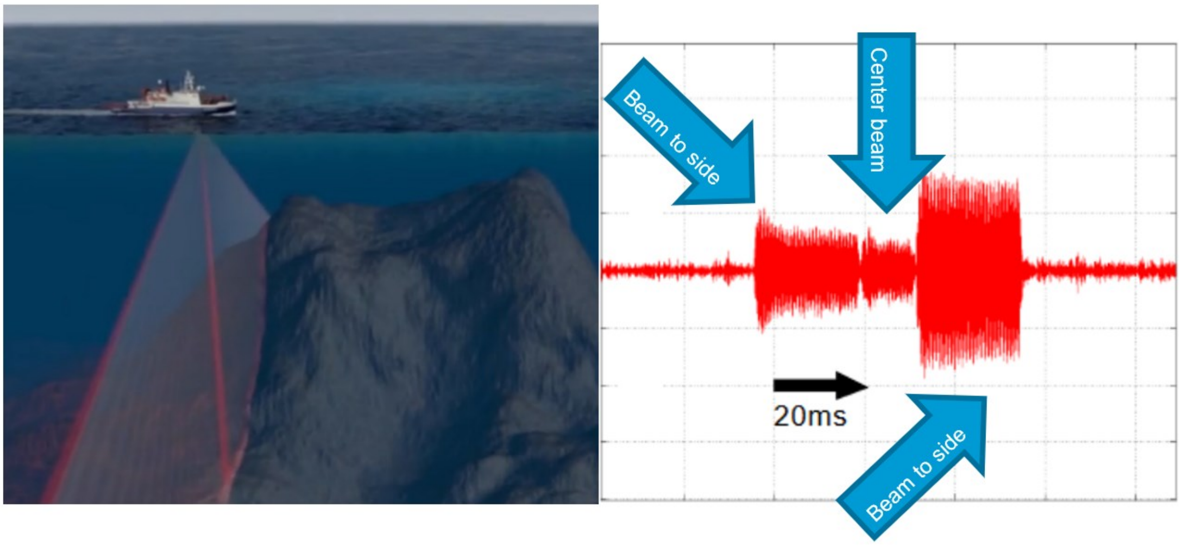
A.1.3 Hydrosweep

Background information

Hydrosweep is a multibeam echosounder for mapping the bathymetry of the sea floor. In addition to its application for navigational safety, it is employed to map the profile of the seafloor abeam of the ship track. The transducer is designed to radiate focused acoustic energy in a downward and transverse direction (Figure A. 7). The sound source is highly directional, therefore primarily receivers in direction abeam of the transducer are exposed to very high level impulses.

Many parameters of the transmitted impulses are configured according to requirements of the area of investigation. Variable parameters such as source level, repetition rate, working frequency, pulse length and number of active beams are summarized in the following tables. The individual settings influence the noise emission. In the following tables there are four configurations compiled for typical water depths in Antarctic research areas targeted by the RV *Polarstern*.

Figure A. 7: Left: Illustration of projected beams, right: Measured underwater received signal of a Hydrosweep pulse. Pulse configuration, recording depth and distance not mentioned in underlying publication. This graph shows characteristics of the pulses: They are composed of three short, continuous blocks, each with approximately constant amplitude. Signals of all three beams Source: Picture on the left taken from the video shown on the website Teledyne Marine (2020). Right: Boebel, et al. (2004).



Source: Teledyne Marine (2020); Boebel et al (2004)

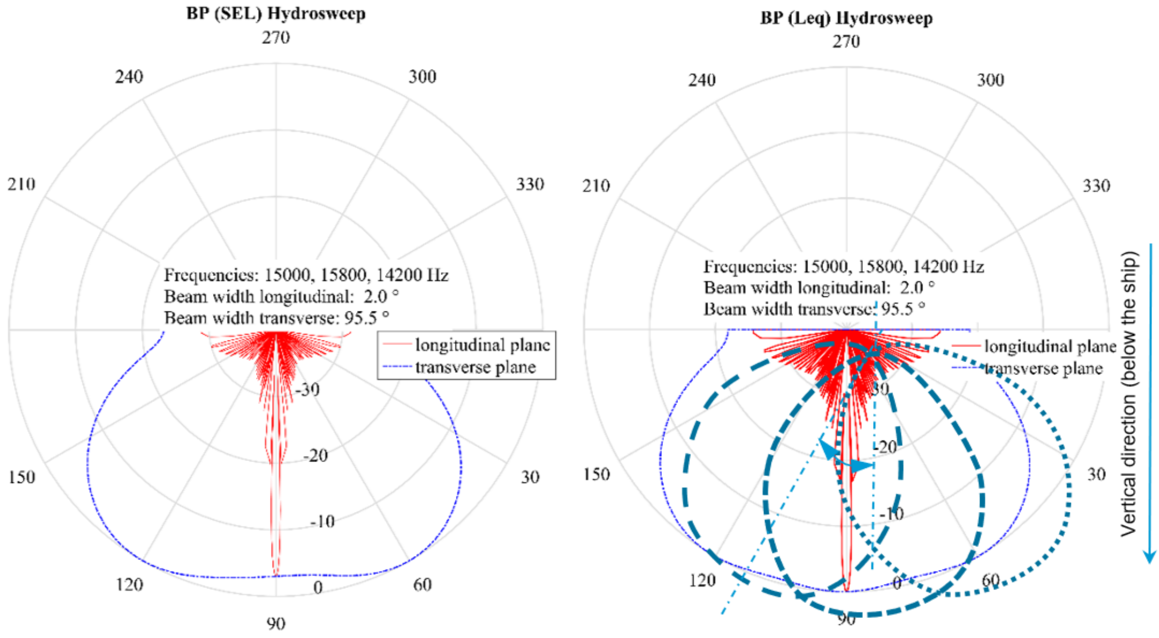
Sound characteristics

Hydrosweep produces short burst signals (Figure A. 7) in order to map the seafloor. These consist of frequency-modulated tones (chirps) at frequencies between 13 kHz and 17 kHz with approximately constant amplitude. The pulses need to contain sufficient acoustic energy so that the back scattered signal from the bottom can be identified in the presence of background noise by a ship mounted receiver. To maximize the backscattered signal, Hydrosweep concentrates the available power in a narrow lobe. This power can be adjusted according to water depth, and is equally applicable to all radiated beams (Table A. 1). Figure A. 9 shows how directivity patterns of sound pressure and sound exposure level differ by transverse and longitudinal plane: Seen from the front, the radiated signal covers a wide angle while from a lateral perspective only a narrow area is exposed (Figure A. 9). The overall directivity chart is composed of multiple beams with different steering angles (Figure A. 8). The sound of these beams is transmitted subsequently to cover a lateral distance of either four times the water depth (based on three beams) or six times the water depth (based on five beams).

For water depths of greater than 1000 m, there are longer pulse durations radiated in transverse direction than to vertical direction (Figure A. 8): due to double pulse length, the lobes of SEL in transverse direction are 3 dB more pronounced and the beam pattern of SEL slightly deviates from Leq (Equivalent continuous sound pressure level) so that more energy is contained in the outer beams. The waveform of pulses with different lengths measured underwater are illustrated in Figure A. 7. In this modelling approach the energy of all lobes is considered according to reported typical operating parameters with reference to the technical specification.

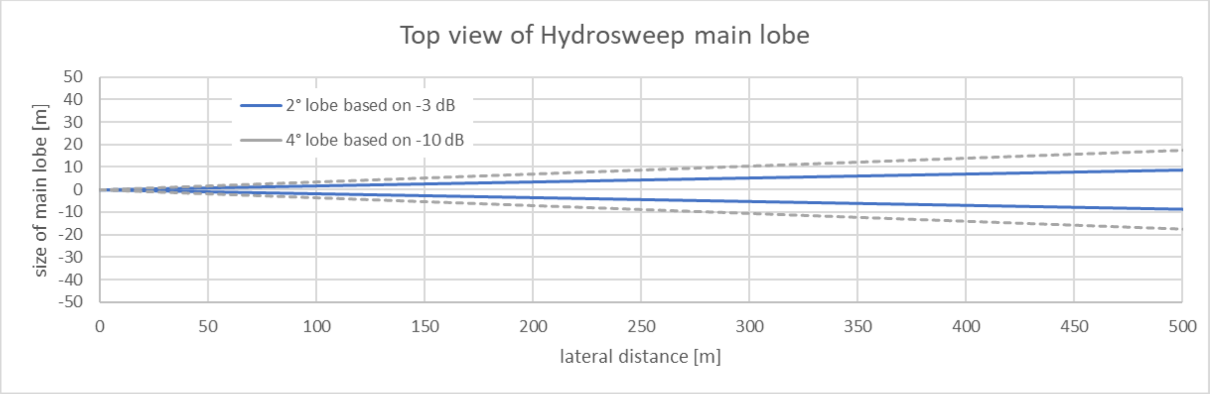
The repetition rate of the Hydrosweep also influences the cumulative SEL which needs to be calculated in a separate step. It can be defined as the rate at which recurrent impulses are produced, and is dependent on water depth. In 'single ping' mode the transducer radiates an impulse and waits until backscatter is received. The system also provides the option for 'multi ping' mode where more than one signal at a time is travelling in the water column. However, according to AWI this is infrequently implemented, therefore these assessments are based on single pings. Repetition rate is therefore based on the travel time of the pulses towards the sea floor and back in transverse direction.

Figure A. 8: Beam patterns (BP) of Hydrosweep with 3 beams. Left SEL, right: RMS levels in 1 m distance. The smooth blue curve shows intensity looking forward in direction of the ship's course. The red curve describes the signal as seen from the ship's side where most acoustic energy is contained in a very narrow lobes. Both graphs show the beam pattern which results from three successively transmitted beams. The direction of the beams can be "steered" by the transducer to be focused towards areas off the vertical direction. The arrow in between the beams marks the steering angle off the horizontal direction. There are three blocks containing different pulse lengths (Table A. 1). Differences between patterns of SEL (left) and sound pressure (right) originate from double pulse length of transverse beams.



Source: Author's own.

Figure A. 9: **Directivity of the Hydrosweep transducer as seen from above, based on -10 dB beam width.**



Source: Author’s own.

Table A. 2: **Technical data of Hydrosweep DS-3.**

Parameter	Value
Sound pressure source level	max. 239 dB re 1 µPa²m² RMS
Working frequency Example	Individual per beam 13 to 17kHz[3] Port side: 15, Centre: 15.8, Starboard: 14.2kHz
Number of beams transverse	3 or 5
Nominal beam width transverse	90° bzw. 140° (- 3dB)
Nomineal beam width forward	2°
Dimensions Transducer (long. x transv.)	3m x 0.3m
Number of Array elements (long. x transv.)	36 x 8

Table A. 3: **Example for depth-dependent configuration of Hydrosweep DS-3.**

Parameter	500 m	1000 m	2000 m	4000 m
Source level [dB] re 1 µPa²m² RMS	230	233	233	239
Impulse length [ms] Port side – Centre – Starboard	7 – 7 – 7	16 – 8 – 16	30 – 15 – 30	36 – 18 – 36
Repetition rate [Hz]	0.98	0.49	0.24	0.12

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[3] There is no raw measured data available to investigate whether the radiated signal contains harmonics of the working frequency. Higher harmonics typically occur when signals are distorted by the amplifier or by the transducer (compara-ble to the sound of a guitar amplifier), therefore the content of harmonics in the signal can vary with radiated power. Investigations on hydroacoustic systems which radiate frequencies below the working frequency are presented by (Deng, et al., 2014).

Technical mitigation

Mitigation of hydroacoustic emissions of Hydrosweep echosounders can be achieved by reassessing the minimum required acoustic transmission. The amount of radiated sound is typically linked to the quality of received, backscattered signals. Possible mitigation options are listed below, with the associated impact on data quality:

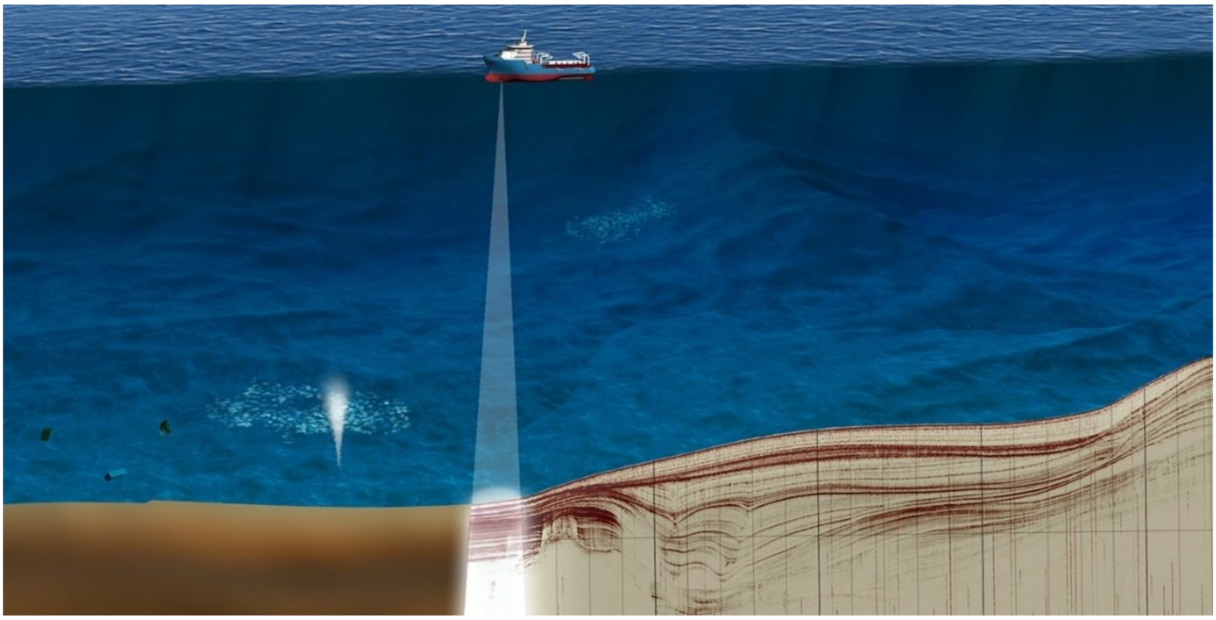
- Minimization of number of transmitted beams (affects swath width)
- Reduction of repetition rate (affects resolution along track)
- Reduction of pulse length (affects quality of backscattered signals)
- Reduction of transmitted power (affects the signal to noise ratio of backscattered signals)

A.1.4 Parasound P70

Background information

Parasound is a hydroacoustic system for imaging sub-bottom structures that occur up to 200m below the sediment top layer. Similar to nautical echosounders, Parasound radiates a sharp downward directed beam (Figure A. 10), using “secondary frequencies” between 2.5 kHz and 5.5 kHz. As described in the following section, these are generated by higher “primary frequencies”. The transducer of the system is mounted in the ship bottom to conduct sub-bottom profiling while the ship is sailing, e.g. during transects parallel to other research activity. It can be operated in conjunction with the Hydrosweep echosounder, but cannot be combined with the fish finders EK60/EK80 due to the frequency overlap.

Figure A. 10: Sketch of Parasound P70 survey.



Source: Teledyne Marine Reson (2020).

Sound characteristics

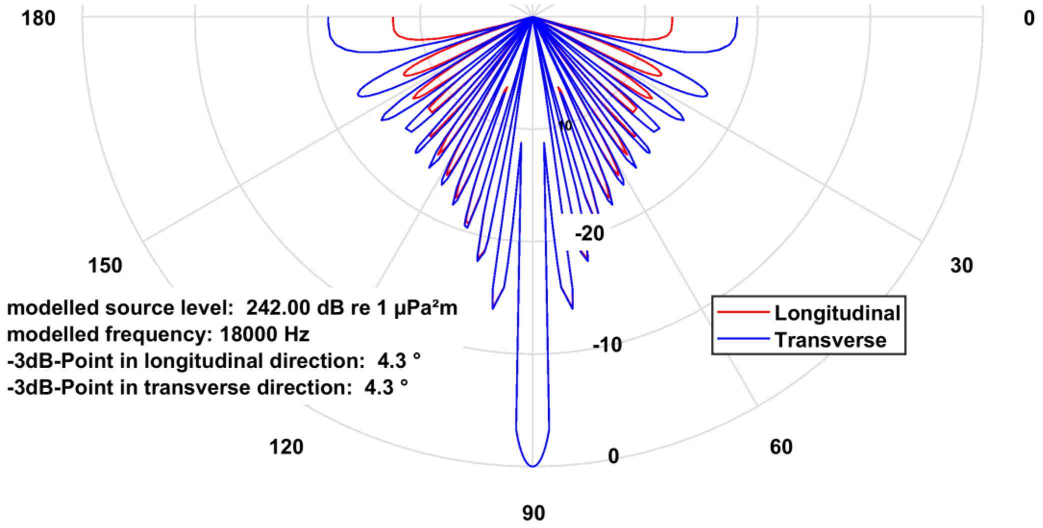
The Parasound P70 device installed on the RV *Polarstern* research vessel applies two primary high frequencies (PHF) simultaneously with same very high power and short duration: one signal at around constant 18 kHz and a second tone configurable from 20.5 to 23.5 kHz. The frequencies of these tones are chosen once for one survey and remain constant over all transmitted pulses with a rectangular pulse shape (amplitude is constant over the pulse). The frequency of the resulting parametric low frequency signal is a function of the two parametric high frequencies. It is approximately 40 dB quieter than the primary signal and consists of a parametric high frequency and a parametric low frequency. It is created in the far field approximately 10 metres below the transducer according to Wendt (2002). The produced signals have a short duration, resulting in the generation of approximately two sine waves of the secondary low frequency signal. Depending on the chosen secondary frequency, this corresponds to approximately 0.5 to 1 ms. There are a wide range of configurations available for the Parasound P70 device, typical settings for investigating Antarctic waters are compiled below (Table A. 4).

Since the absolute level of the main beam is high (source level: 242 dB re 1 μPa^2m^2 RMS, approximately 212 dB re 1 μPa^2s, 1m SEL), side lobes as sketched in Figure A. 11 can have significant impact in the near field: In a wide angular range the radiated signal is approximately 20 to 30 dB quieter than in tha main vertical direction. This results in approximately 185 dB re 1 μPa^2s source level which is attenuated by spherical spreading down to 165 dB re 1 μPa^2s in 10 m distance and further down to 145 dB re 1 μPa^2s in 100 m distance. The direction of the main lobe is compensated for ship motion by beam steering, therefore it is always pointing vertically downwards.

Table A. 4: Technical data of Parasound P70.

Parameter	Typical configuration according to PS014	Possible range according to data sheet
Source level (dB re 1 μPa^2m^2 RMS)	242 dB primary high freq. SPL of secondary not available	Max 245 dB primary high freq. Max 206 dB secondary low freq.
Primary high frequencies	18 and 20.5 - 23.5 kHz	18 and 20.5 - 33 kHz
Secondary parametric low frequency	4 kHz and 40 kHz	0.5- 7 kHz and 37 -43 kHz
Number of pulses in water columns	Single pulse 0-100 m Quasi-equidistant multi ping <100m	Up to 16 simultaneous pulses
Width of main lobe transverse	4.3°	4.3°
Width of main lobe forward	4.3°	4.3°
Transmission power	70 kW	70 kW
Repetition interval	2 Hz	Max 20 Hz interval
Pulse length	0.5 ms	0.17 ms – 25 ms
Pulse type and shape	Continuous sine wave, rectangular pulse	Continuous sine wave, rectangular pulse

Figure A. 11: Beam pattern of Parasound P70 primary frequency 18 kHz.



Source: Author’s own.

Technical mitigation

Mitigation of hydroacoustic emissions of Parasound echo sounders can only be achieved by modification of operating parameters. These are typically linked to data quality of the system’s output. Necessary minimum requirements should be discussed with entrusted geologists to investigate whether Parasound settings during individual voyages can be reduced below default values.

Possible parameters to reduce received SEL values in comparison to negative impacts on data quality are:

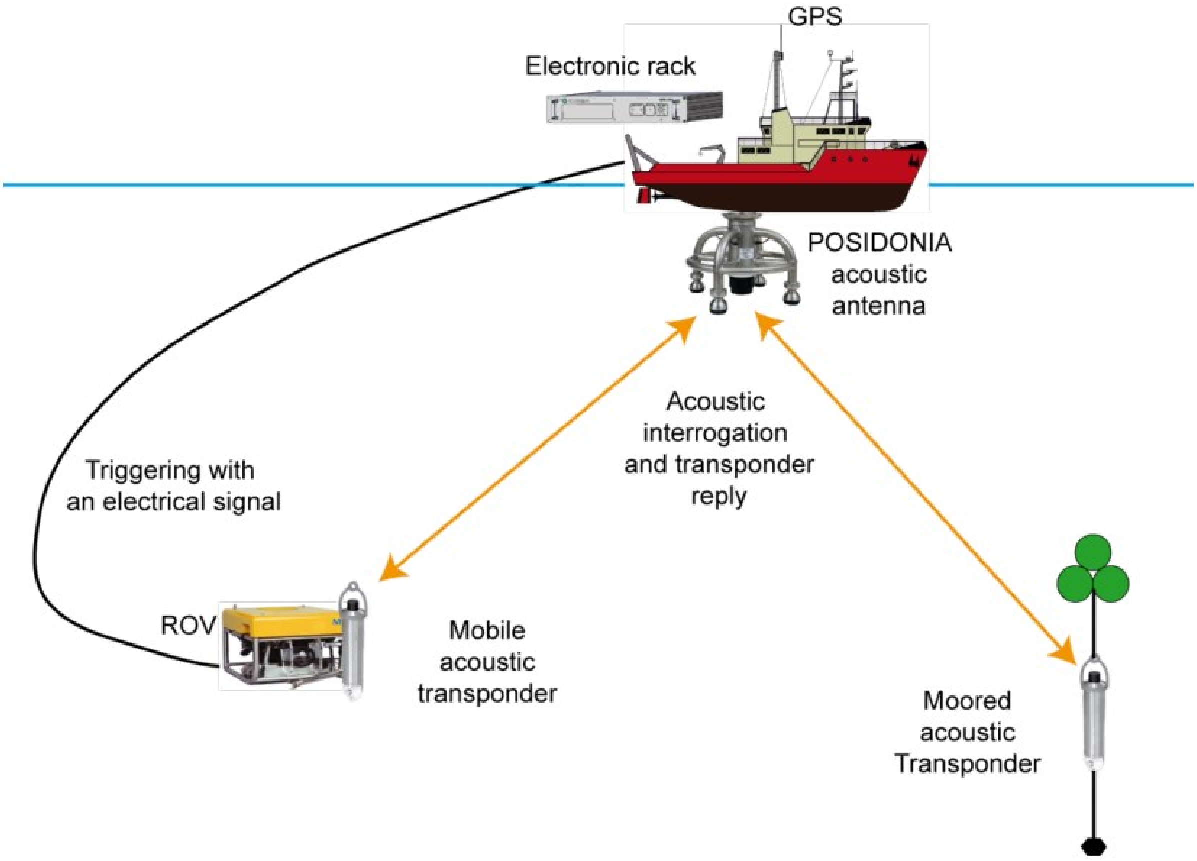
- Reduction of source level (reduces penetration depth of the secondary signals).
- Reduction of repetition rate (affects resolution along track).
- Reduction of pulse length (affects quality of backscattered signals).

A.1.5 Posidonia 6000

Background information

Posidonia 6000 is an Ultra Short Baseline (USBL) positioning and remote-control system for underwater equipment. An UBSL positioning system is made of a small array of receivers which are integrated in one small unit. This system can be deployed from a moving ship, it does not require moored reference positions so that acoustic signals are only transmitted from the ship-mounted antenna and from one deployed device. Posidonia 6000 is a ship mounted acoustic array that consists of two units: a receiving antenna and a transducer, which communicate with underwater beacons via hydro-acoustic signals (Figure A. 12). Communication between these components is designed as a dialogue between antenna and beacon. For positioning of underwater equipment, the antenna broadcasts a specific chirp which is received by the beacon. Upon receipt, the beacon replies with a different chirp signal. The received signal by the antenna of the acoustic array is used to calculate bearing and distance between antenna and beacon. Some beacons are designed acoustic releasers that can detach mooring lines from their anchors by acoustic remote control.

Figure A. 12: **Sketch of communication between acoustic array and transponders (beacons), used in the positioning system Posidonia 6000.**



Source: Posidonia 6000 manual.

Onboard the RV *Polarstern*, the 'search mode' is the most frequently used communication setting, however there are multiple mode options for tracking underwater moving equipment or for remote control of stationary moorings:

- **Responder mode** (two-way hydroacoustic communication) for tracking of equipment without cabled (umbilical) connection: A hydroacoustic interrogation chirp is transmitted by the acoustic array. Upon receipt of this specific signal, the beacon replies with a hydroacoustic chirp which is received by the antenna of the acoustic array to calculate distance and bearing
- **Transponder mode** (one-way hydroacoustic communication) for tracking of equipment with wired datalink: An interrogation pulse is transmitted electronically by cable. The beacon replies with a hydroacoustic chirp which is received by the antenna of the acoustic array.
- **Search and release** (remote control) mode for remote control of releaser systems: This operation is conducted to find and release stationary moorings. The vessel-mounted acoustic array is activated, transmitting signals in regular intervals while the vessel is approaching the location of a mooring. Once the system is found and the vessel is located in vicinity, release communication is initiated.

Sound characteristics

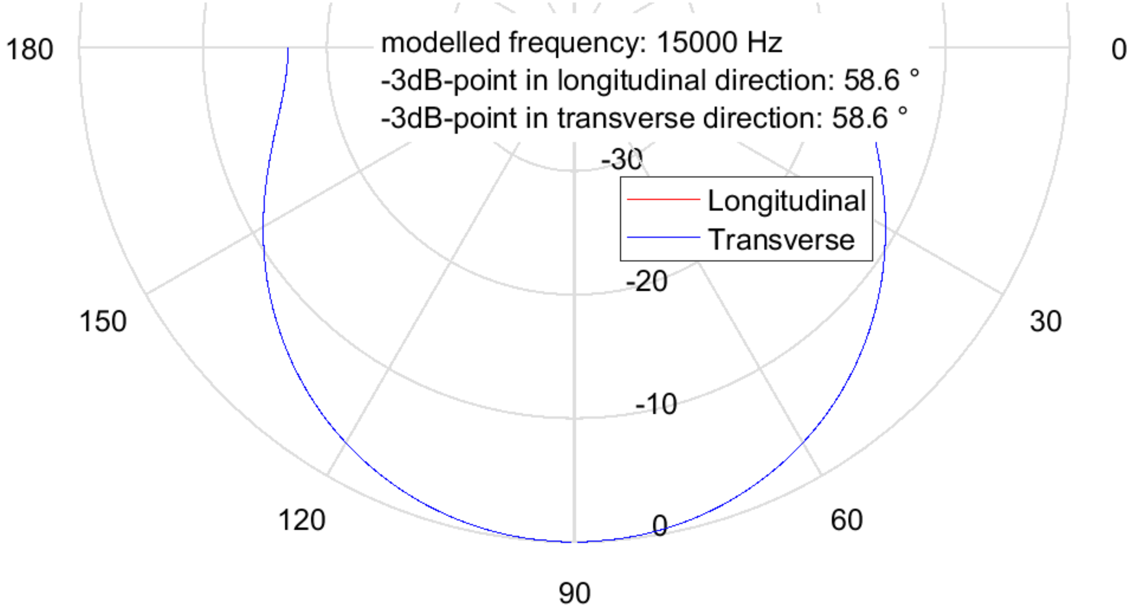
Communication between components in the Posidonia positioning system is made by chirp signals or by frequency shifted tones between 10 ms and 90 ms length from 14 kHz to 18 kHz. There are only specified values available for description as listed in Table A. 5. Measured spectra or spectrograms to illustrate temporal characteristics of the communication are not contained in published documents. However, this positioning system is only used in special occasions while moorings are deployed and retrieved, it can additionally be used for tracking of ROVs. During transit of the ship the transducer remains switched off so that acoustic emissions are limited to a time window of several hours, depending on the work progress in the field.

All communication signals in the Posidonia system are transmitted hemispherically to ensure that signals are received in any spatial alignment of the devices to each other. The source levels of acoustic array and beacons are at least 40 dB lower than those of directional sources (Hydrosweep, Parasound) for mapping of the sea floor. However, Posidonia transmits in all directions so that a comparatively large area is ensonified. This wide range of transmission angles needs to be taken into account for assessment of cumulative SEL. Source levels of acoustic array and beacon are identical.

Table A. 5: Posidonia 6000 characteristics of transmitted signals.

Parameter	Surface acoustic array	Underwater beacon
Source level acoustic array	191 ± 4 dB re 1 µPa^{2}m^2 RMS	191 ± 4 dB re 1 µPa^{2}m^2 RMS
Operating frequency	16 kHz ± 3 kHz Bandwidth 14 – 18 kHz (specsheet)	14.5 – 17.5 kHz
Source depth	Approx. 10 m (in ship bottom)	Depending on application, typically close to seabed
Signal length of release command	8 x 2 pings, each 90 ms length, repetition of this sequence each minute	Acknowledgement by 1 ping, 10 ms length
Signal type for release command	Frequency-shifted tones,	Frequency-shifted tones
Repetition interval for positioning	Min 2 seconds, typical between 4 and 8 seconds	Min 2 seconds, typical between 4 and 8 seconds
Pulse length for positioning	Single chirp, 10 ms	Single chirp, 10 ms

Figure A. 13: **Hemispherical beam pattern of Posidonia surface acoustic array. In this case, transverse and longitudinal pattern are same due to hemispherical transmission. Therefore, the red line of the longitudinal pattern is covered by the blue line.**



Source: Author's own.

Technical mitigation

Mitigation of hydroacoustic emissions of the Posidonia 6000 system requires modification of the operation profile. Since transmitted events ("pings") are radiated at a constant source level and constant length, only the parameters to adjust repetition rate may be modified:

- In **search mode** which is typically applied by AWI, the interval between transmitted sequences can be prolonged. This modification may prolong the search procedure, and therefore requires prior consultation with experienced operators and tested to determine its feasibility.
- In **transponder mode** and **responder mode** the cumulative transmitted energy is determined by the transmission interval. Prolonged intervals result in reduced accuracy of the tracking procedure. Acceptable limits of this data loss need to be discussed with operators of the equipment.

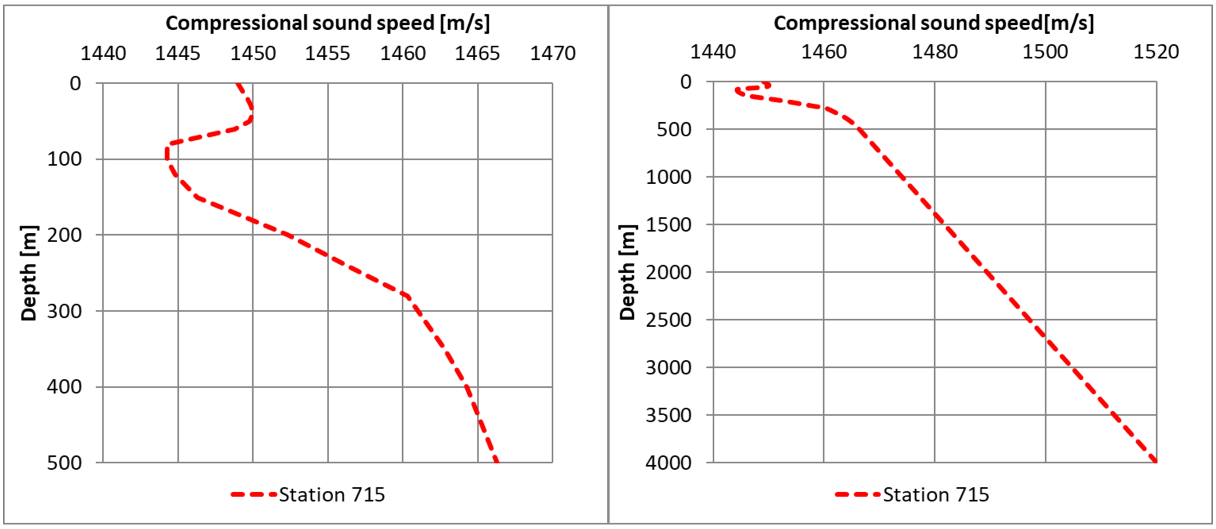
A.2 Noise propagation in Antarctic waters

A.2.1 Types of Antarctic habitat for noise propagation modelling

As aforementioned, this guidance document refers to noise propagation in specific Antarctic environments. Key habitats are limited to those previously defined to manage the complexity of the Antarctic environment. Exploration of Antarctic waters by the AWI has mostly occurred within the Weddell, Amundsen and Bellingshausen seas. Regions have been grouped into shallow waters, characterised by average depths of 500m, and deep-water regions of approximately 4000m depth. All selected environments are considered with typical parameters of the Amundsen and Bellingshausen Sea, modelled constant over range (water depth, sound speed profile as shown below and sediment type) here to display average conditions for typical scenarios of geological research in Antarctic waters. This summary is limited to two characteristic environments with range-independent bathymetry as seismic investigations of continental slopes were conducted to a lesser extent in Antarctica. For continental slopes it can generally be said that sloped bathymetry can affect sound propagation in very different ways, primarily depending on steepness of the slope and on the location of the sound source relative to the slope. For source location above the slope, the backscattered signal can be coupled into a sound channel which significantly increases long range propagation. In other cases, the characteristics of the slope affects the temporal character of pulsed sources. Especially for airguns, the impulsive sounds can be distorted to a length of several seconds. Examples for sound propagation over slopes and signal distortion over very long ranges are found in Wölfing, et al. (2021).

Based on the regions previously researched by AWI, there are two types of applicable sound speed profiles for Antarctic waters regardless of the water depth as reported by Boebel et al. (2009). In the Weddell Sea, sound velocity minimum is located at the surface, resulting in upwards refracting characteristics so that sound is directed towards the sea surface where each reflection involves scattering and attenuation. Conversely, in the Amundsen and Bellingshausen seas, sound velocity minimum is located at approximately 100m, resulting in a surface duct (Figure A. 14) with less scattering and less attenuation than encountered in upwards refracting conditions. For long-range sound propagation, the sound speed profile in the Amundsen and Bellingshausen Seas results in less attenuation at the depth of the surface duct while a shadow zone with poor propagation can occur below the duct. The scenario of sound trapped in a surface duct is therefore chosen for further modelling to reflect a precautionary approach for considering sound exposure of marine mammals, which depend on regular contact to air. Breathing at the surface always requires diving through the duct when diving at depths below the surface duct.

Figure A. 14: Sound speed profile in Amundsen and Bellingshausen Seas, Austral Summer. Left: for 500 m deep ("coastal shallow"), right: 4000 m deep ("deep water") scenario.



Source: Author's own.

Geoacoustic parameters

There is little information available on properties of sediments in these areas, but the seabed has previously been described as a soft top layer with significant fractions of mud and sand by Boebel et al. (2009) and Jerosch et al. (2015).

For modelling the noise emission and propagation for the two chosen environments, model parameters were chosen according to values in the impact assessment by Boebel, et al. (2009) as this study was prepared based on specific knowledge of geology in the Antarctic seas where seismic profiles are collected by RV *Polarstern*. The authors applied a soft sediment according to Table A. 6 which is modelled as an infinite halfspace. This assumption in combination with negligible compressional wave attenuation of 0.00002 (2e-5) dB per wavelength[4] is considered a precautionary approach. In comparison to sediments with typical compressional wave attenuation between 0.1 and 1 dB per wavelength described by Jensen, et al. (2011) the setup by Boebel et al. (2009) leads to higher received levels.

Table A. 6: Geoacoustic parameters used in the numerical acoustic propagation model.

Layer	Thickness (m)	Wet bulk density (kg / m³)	Compressional wave speed (m/s)	Compressional wave attenuation (dB / λ)	Shear wave speed (m/s)	Shear wave attenuation (dB / λ)
Clay	∞	1450	1600	2e-5	0	0

Applied averaging procedures

Numerical modelling was conducted to obtain a graphical display of either propagation loss or received levels over range and depth. These values are presented in the graphs below. A graphical format with isopleths was chosen which allows easy and accurate reading of values. The results are shown for broadside direction in the plane abeam of the noise source. Results for Airguns and ship noise are averaged in full octave bandwidth, see Wang, et al. (2014) for further explanation of smoothing results by means of averaging. The results for ship noise were calculated for omnidirectional sources as explained in section A.1.1 with frequency resolution in centidecades (10 values per 1/3 octave) and energetically averaged in full octave bins.

Modelling of airguns was prepared in a different context where effects of a moving source were considered. The changing geometry of the moving source introduced sufficient averaging for values in that context so that additional averaging over frequency was not required for smoothing of the results. Propagation loss for airguns was therefore calculated only in resolution of 1 value per 1/3 octave. However, the modelled propagation loss from this earlier project was re-used in this review of anthropogenic underwater noise sources in Antarctica. This presentation summarizes only noise emissions of the sources without discussing cumulative effects. For this reason, there are no moving sources considered in the context here so that the results of modelled sound propagation of airguns show a rough pattern without smoothing of a moving source in large distances.

Source-specific propagation modelling

The numerical propagation models were chosen according to the different characteristics of the noise sources. This annex contains results which were calculated with following different methods:

High frequency, directional sources (Hydropsweep, Parasound, Posidonia) were modelled in two steps:

1. The 3D beampattern is calculated based on technical data of the transducer according to Sherman & Butler (2007)

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[4] The publication describes compressional wave attenuation by means of a quality factor: “a negligible attenuation for P- and Swaves quantified by the quality factors QP = QS = 1.5 × 10^-6 were chosen for the sea floor” Boebel, et al. (2009) p. 17.This corresponds to -0,00002 (2e-5) dB per wavelength.

2. Directive sound propagation is modelled by spherical spreading (20 log (range)), acoustic intensity is scaled according to the calculated beampattern. This approach considers frequency-dependent absorption according to Robinson (2015). Reflectivity of the seafloor was modelled with the software BOUNCE which is available through the acoustic toolbox AcTUP.

Sound propagation of **Airguns** was modelled in a context where consideration of range-dependent bathymetry should be possibly treated in follow-on questions. A suitable numerical model for range-dependent scenarios at low frequencies interacting with an elastic seabed is the parabolic equation code RamGEO. It solves the Helmholtz equation for elastic waves based on a split Padé approximation. Since this approximation leads to errors at steep angles off the main propagation direction, Jensen, et al. (2011), p. 477 ff.), received levels below the source will be overestimated. However, this trade-off between capability of range-dependence and biased results below the source was acceptable in the context for which the results were initially modelled. RamGEO is contained in the toolbox AcTUP, it is applied here in the frequency range below 250 Hz as it requires extensive computation time at higher frequencies.

The propagation model for **ship noise** was based on the assumption that impact assessments potentially take into account effects in close proximity to the noise source as well as contributions at large distances. For this reason, all areas shall be covered by the propagation model without errors due to approximation techniques which were previously explained for the code RamGEO. In the context of this pamphlet, consideration of range-independent propagation is sufficient. Therefore, the wavenumber integration code Scooter & Fields was selected to compute low frequency propagation. The code is split in function “Scooter” which calculates depth-dependent Green’s functions in a horizontally layered environment. These Green’s functions are integrated by the function “Fields” by using a Fast Fourier Transform. The publicly available version of Scooter & Fields can only handle range-independent environments. It is applied in the frequency range below 100 Hz as it tends to numerical instability at higher frequencies.

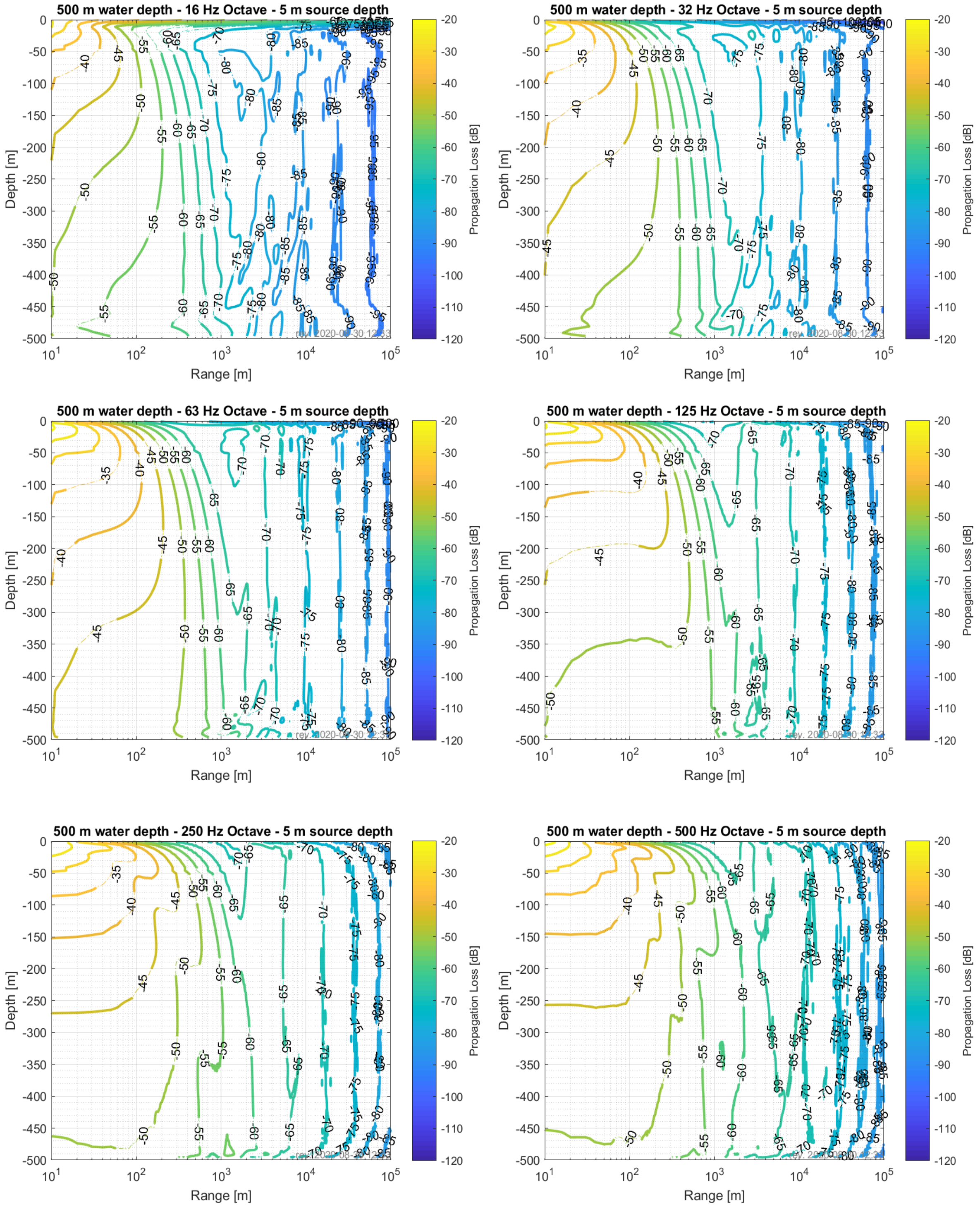
Sound propagation at higher frequencies above the limitations of the codes RamGEO and Scooter & Fields was modelled by the beamtracing code Bellhop. This is a beamtracing code which traces the paths of propagation beams in a stratified medium. In the context here it was applied to calculate semi-coherent propagation loss where major interference patterns due to surface and bottom reflections are conserved while patterns with finer scale at higher frequencies are smoothed out. It includes a frequency-dependent absorption model according to Thorp (1965).

A.2.2 Sound propagation model: omni-directional sound source

Here, the noise propagation from the research vessel RV *Polarstern* is modelled as an example of omni-directional sound propagation in Antarctic waters, in both deep water habitats and shallow coastal waters. Results are summarized in Figure A. 15 to Figure A. 18.

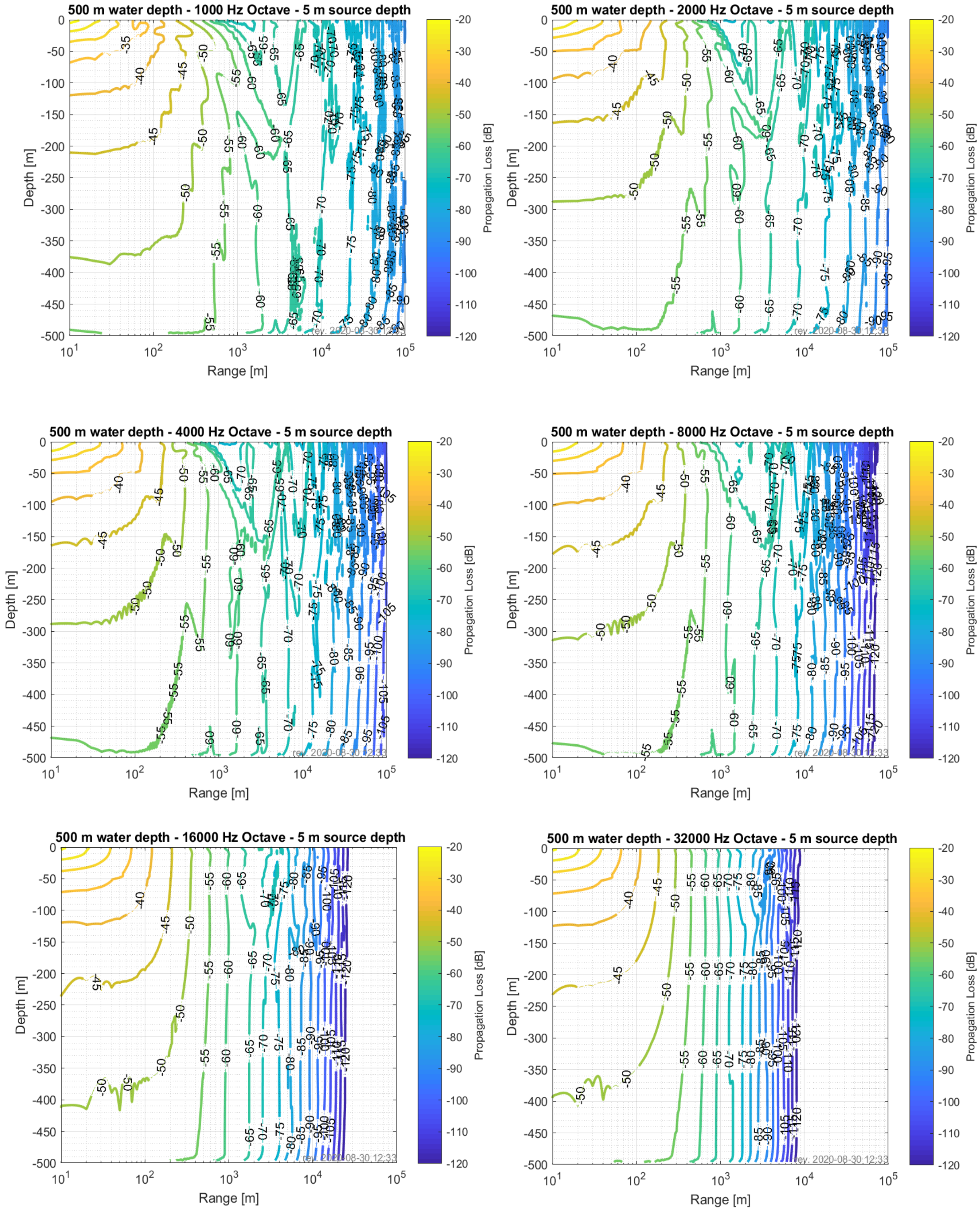
Shallow water, coastal habitat

Figure A. 15: Results for propagation loss of ship noise in a shallow water, coastal environment with 500 m water depth, 16 Hz to 500 Hz octaves.



Source: Author’s own.

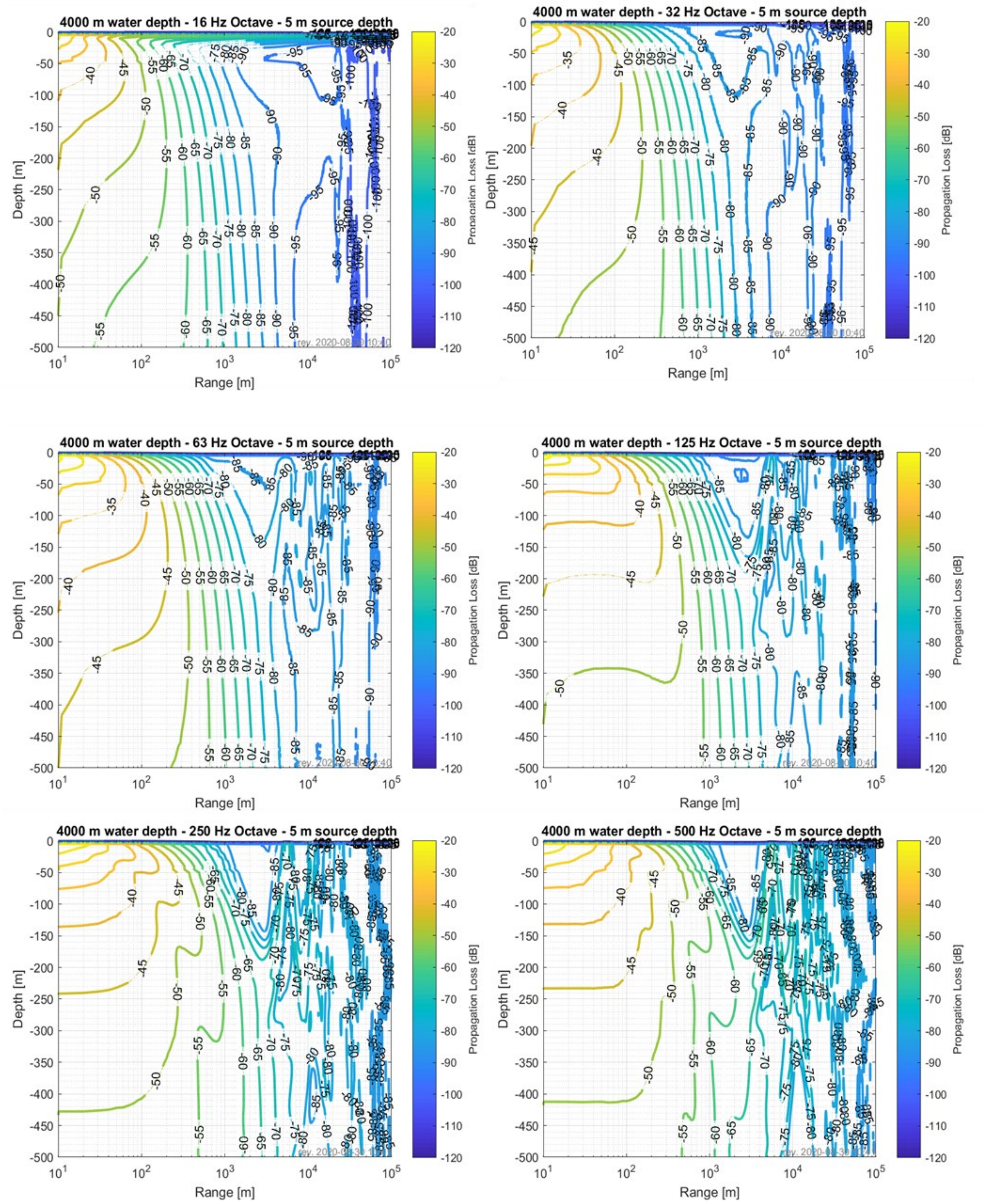
Figure A. 16: Results for propagation loss of ship noise in a shallow water, coastal environment with 500 m water depth, 1 kHz to 32 kHz octaves.



Source: Author's own.

Deep water, flat-bottomed habitat

Figure A. 17: Results for propagation loss of ship noise in a deep water, flat bottom environment with 4000 m water depth, 16 Hz to 500 Hz octaves. Results are only shown for the top 500 m where most receptors are expected to be present.



4000 m water depth - 16 Hz Octave - 5 m source depth

4000 m water depth - 32 Hz Octave - 5 m source depth

4000 m water depth - 63 Hz Octave - 5 m source depth

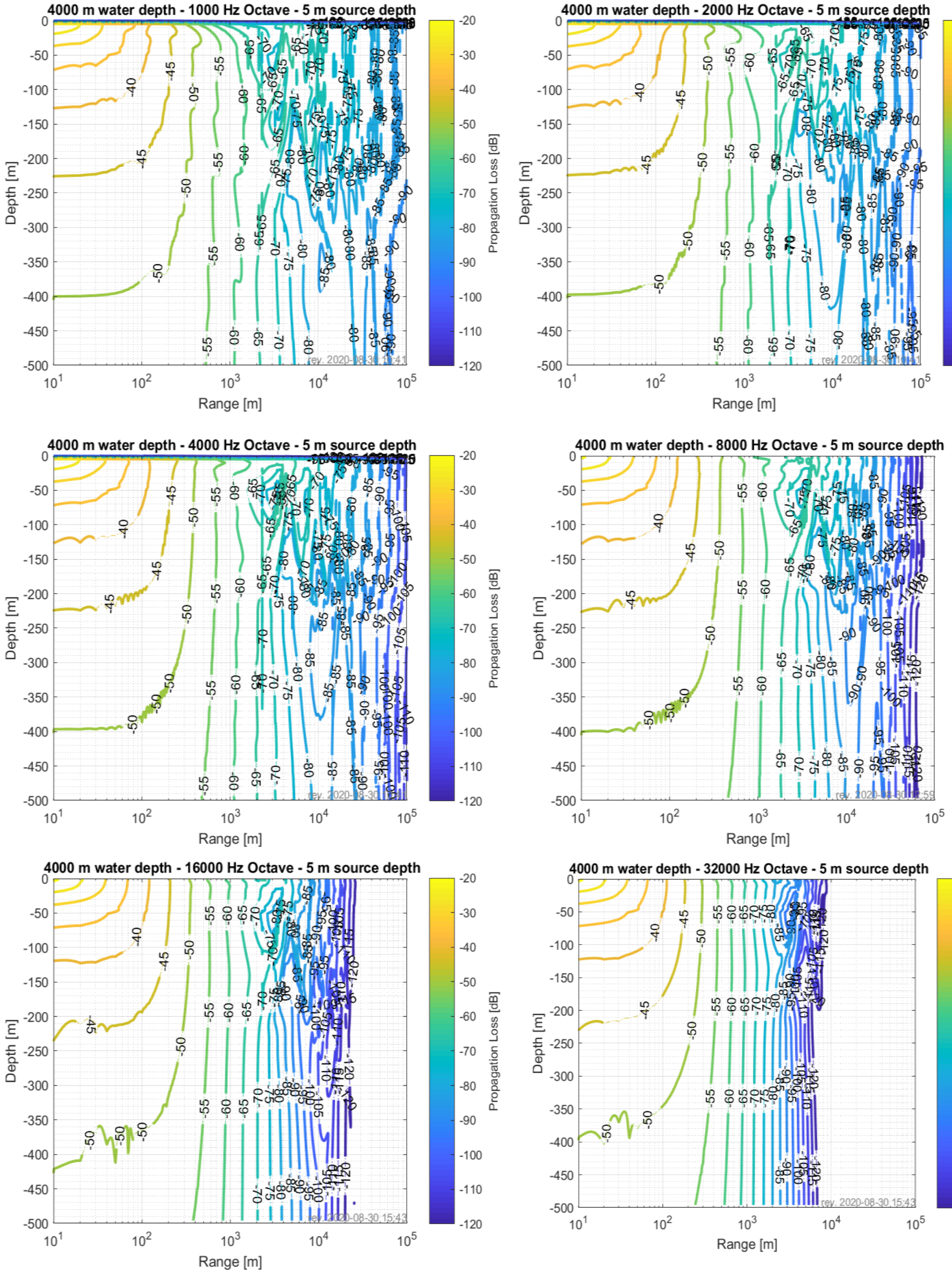
4000 m water depth - 125 Hz Octave - 5 m source depth

4000 m water depth - 250 Hz Octave - 5 m source depth

4000 m water depth - 500 Hz Octave - 5 m source depth

Source: Author's own.

Figure A. 18: **Results for propagation loss of ship noise in a deep water, flat bottom environment with 4000 m water depth, 1 kHz to 32 kHz octaves. Results are only shown for the top 500 m where most re-ceptors are expected to be present.**



Source: Author’s own.

Instructions for calculation of received levels

Received levels are calculated as follows:

1. Look up Monopole source level (SL) for selected 1/3 octave frequency in Figure 2.
2. Identify corresponding full octave centre frequency
3. Look up Propagation loss for this frequency band and corresponding depth (500 m or 4000 m) in the graphs shown in section A.2.3.
4. Read numerical of Propagation Loss (PL) value for position (horizontal distance and depth) of receiver
5. Calculate received level (RL): RL = SL - PL
6. If required: Calculate broadband received level from the energetic sum of the 1/3 octave spectrum:

$$L_{p,broadband} = 10\log_{10} \sum_{i=1}^{n\ 1/3\ octaves} 10^{\frac{L_i}{10}}$$

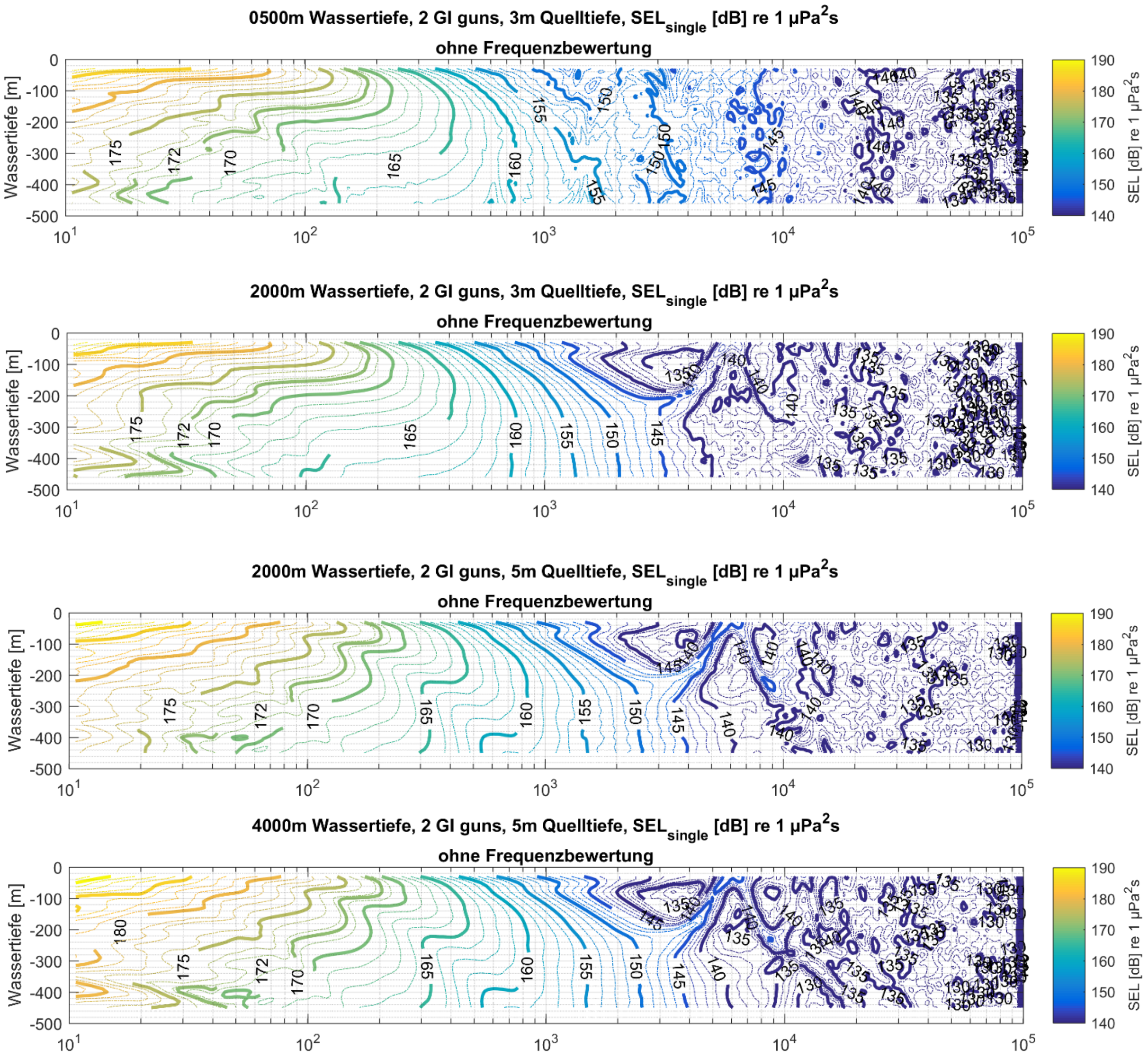
A.2.3 Sound propagation model: Source specific

Noise propagation models are presented for the different sound sources presented in sections A.1.2 to A.1.5, in coastal and deep-water conditions, respectively.

Propagation of seismic airguns

The broadband results in figures below were calculated based on 1/3 octave centre frequencies for seismic airguns as presented in section A.1.2. There is no averaging over range applied, therefore the graphs appear more ‘patchy’ than propagation loss shown for ship noise (see Applied averaging procedures).

Figure A. 19: Modelled received SEL levels for application of 2 GI guns in water of different depths. Received SEL levels of single shots are shown within the top 500 m only.



0500m Wassertiefe, 2 GI guns, 3m Quelltiefe, SEL_{single} [dB] re 1 µPa²s ohne Frequenzbewertung

2000m Wassertiefe, 2 GI guns, 3m Quelltiefe, SEL_{single} [dB] re 1 µPa²s ohne Frequenzbewertung

2000m Wassertiefe, 2 GI guns, 5m Quelltiefe, SEL_{single} [dB] re 1 µPa²s ohne Frequenzbewertung

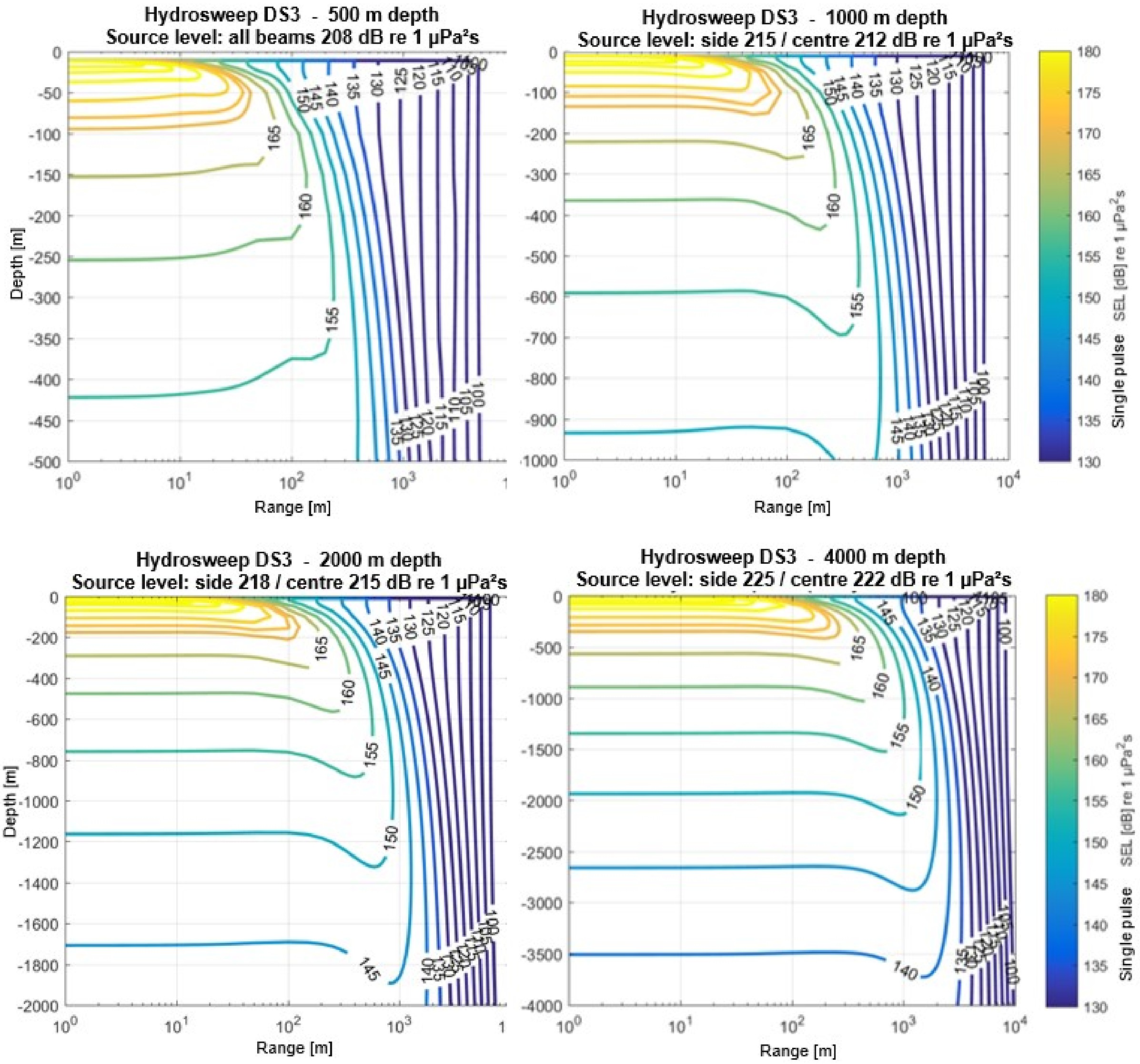
4000m Wassertiefe, 2 GI guns, 5m Quelltiefe, SEL_{single} [dB] re 1 µPa²s ohne Frequenzbewertung

Source: Author’s own.

Propagation of Hydrosweep DS3

The results in figures below were calculated based on typical operating parameters of Hydrosweep DS3 as presented in section A.1.3. Input values of the calculations are summarized above each graph.

Figure A. 20: **Received single pulse SEL values of Hydrosweep multibeam echosounder in environments of different water depths. The results are calculated for respective operating condition (SEL source level in caption according to RMS source level & pulse length in Table A. 2).**



Hydrosweep DS3 - 500 m depth
Source level: all beams 208 dB re 1 µPa²s

Hydrosweep DS3 - 1000 m depth
Source level: side 215 / centre 212 dB re 1 µPa²s

Hydrosweep DS3 - 2000 m depth
Source level: side 218 / centre 215 dB re 1 µPa²s

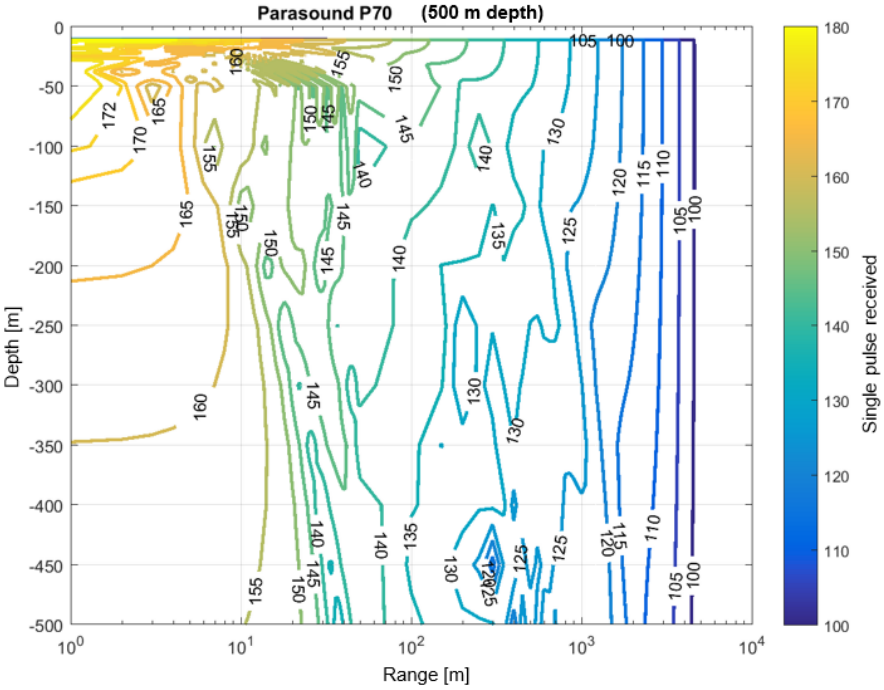
Hydrosweep DS3 - 4000 m depth
Source level: side 225 / centre 222 dB re 1 µPa²s

Source: Author’s own.

Propagation of Parasound P70

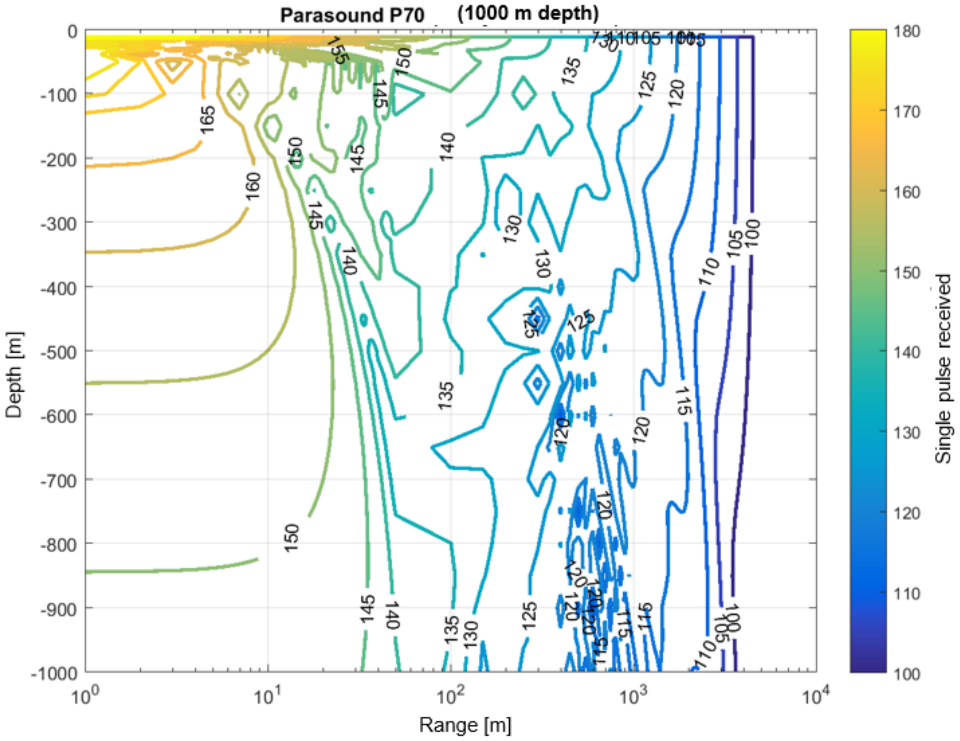
The results in figures below were calculated based on typical parameters of Parasound P70 as presented in section A.1.4. Secondary low frequencies are not considered here since these contribute less than 0.001 dB to the overall received levels.

Figure A. 21: Received single pulse SEL of Parasound in 500 m deep water, primary frequencies 18 kHz and 20.5 kHz, source level 242 dB re 1 µPa²m².



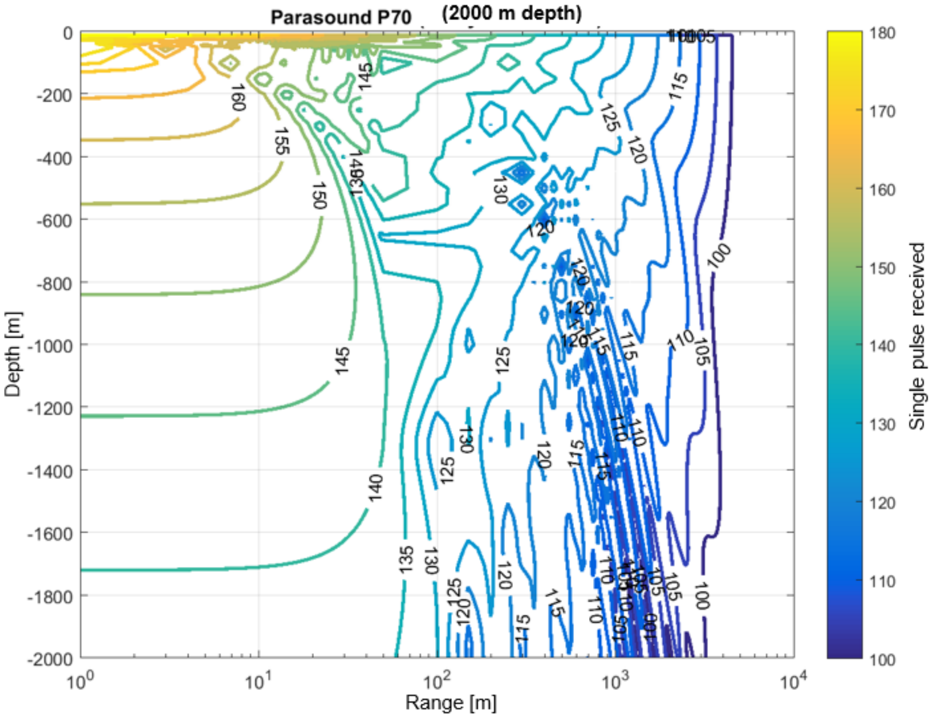
Source: Author’s own.

Figure A. 22: Received single pulse SEL of Parasound in 1000 m deep water, primary frequencies 18 kHz and 20.5 kHz, source level 242 dB re 1 µPa²m².



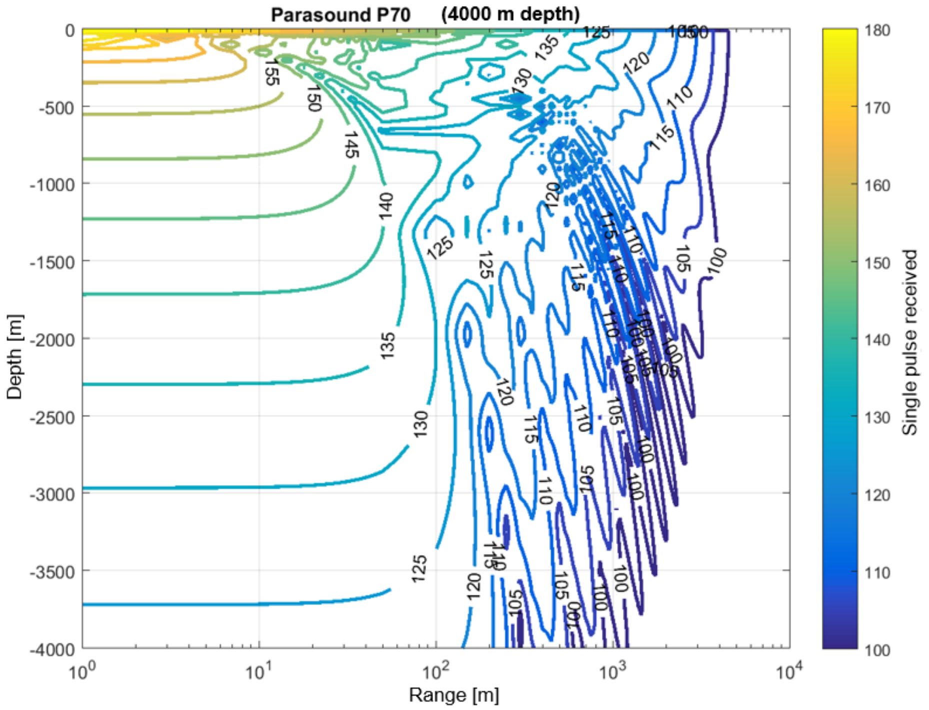
Source: Author’s own.

Figure A. 23: Received single pulse SEL of Parasound in 2000 m deep water, primary frequencies 18 kHz and 20.5 kHz, source level 242 dB re 1 µPa²m².



Source: Author’s own.

Figure A. 24: Received single pulse SEL of Parasound in 4000 m deep water, primary frequencies 18 kHz and 20.5 kHz, source level 242 dB re 1 µPa²m².

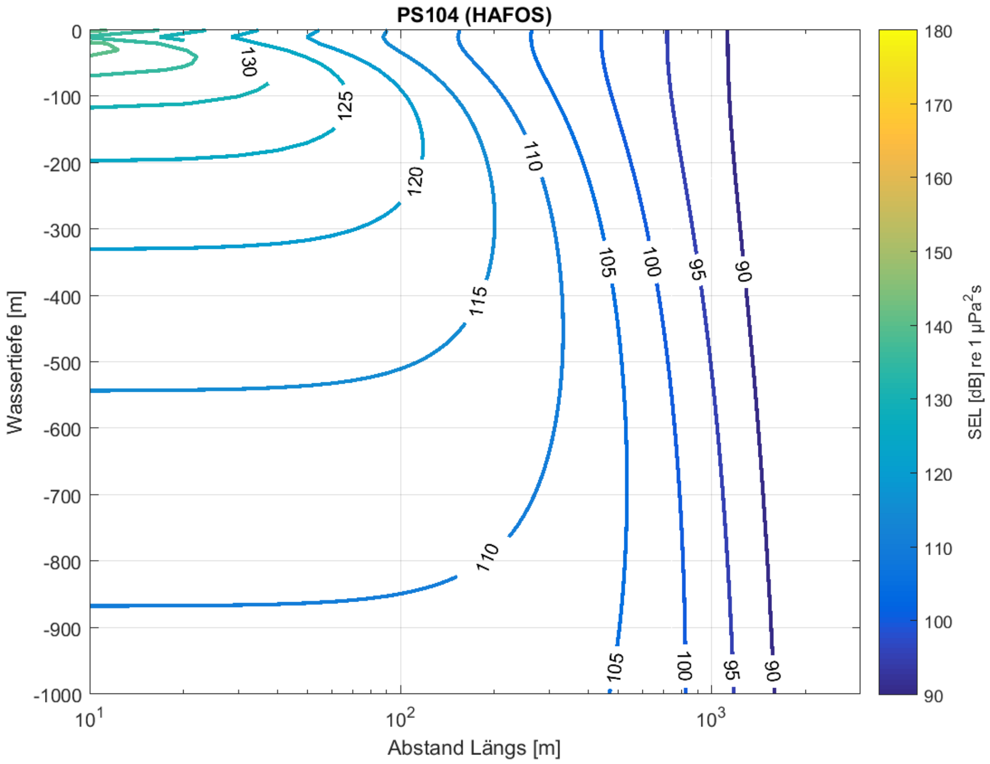


Source: Author’s own.

Propagation of Posidonia 6000

The results in figures below were calculated based on typical parameters of Posidonia 6000 as presented in section A.1.5.

Figure A. 25: Received SEL levels of single pings for Posidonia surface unit in search mode.



Source: Author’s own.

A.3 Appendix to Annex 1 - Conversion procedure for radiated noise levels to monopole source levels

All data for the assessment of ship noise is available in the format of radiated noise levels (RNL): The measurement results of the ship Polarstern were reported by Kraus, et al. (2011) as RNL and the limit curves discussed further below are also defined as RNL. These can only be applied for further modelling if converted to monopole source levels (MSL).

In chapter A.1.1“Ship noise” so-called limit curves were introduced to describe radiated noise levels for cruise ships and research vessels. These limit curves can be applied as a contract requirement for newbuilding projects. The ship is to be designed in a way that its radiated noise will not exceed the limit curve. This requirement is typically checked by predictions during design phase and by underwater noise measurements during sea trials. The resulting radiated noise levels of these measurements are compared with the limit curve. The ship has passed the test if the measured spectrum is below the limit curve in all frequency bands. In case of exceeded values the owner can either refuse acceptance of the ship, re-negotiate cost or require rectification of the acoustic shortcomings.

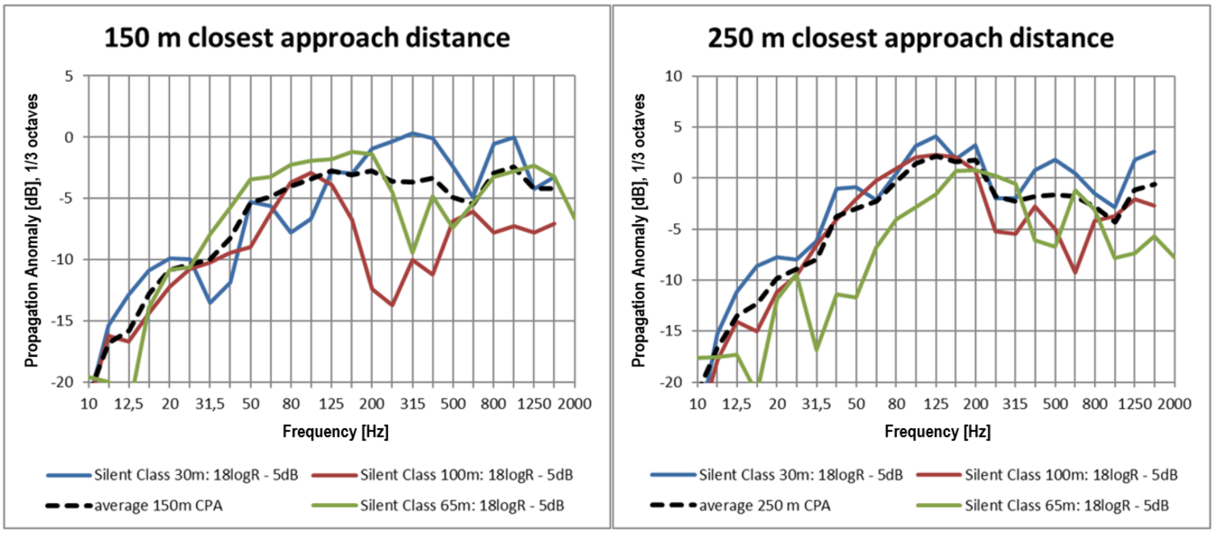
The limit curve is only valid in combination with measured results that were collected in a specific measurement geometry. In case of DNVGL Silent Class the closest point of approach of the ship passing the hydrophone shall be chosen between 150 m and 250 m. Water depth is valid between 30 m and 100 m. In all cases the hydrophone shall be moored 20 cm above the seabed. Distance correction is calculated by 18 log (R) - 5 dB which leads to a radiated noise level.

The conversion from radiated noise level to monopole source level is made by numerical modelling of propagation loss and assumption of required input. A source depth of 5 meters is estimated for cruise ships and research vessels. The measurements are likely to be conducted on sandy bottom, 10 results are modelled per decidecade to account for averaging. Results shown in Figure A. 15 to Figure A. 18 (section A.2.2) were calculated according to the modelling and averaging procedures explained in the previous section for two 150 m and 250 m closest point of approach, three water depths 30 m, 65 m and 100 m in the valid range. A propagation anomaly to describe deviations from spherical spreading according to (Urick, 1982) was calculated for each modelled propagation loss with respect to the distance correction formula as stated in the measurement procedures of DNVGL Silent class: Propagation Anomaly = PLmodelled - 18 log10 (R) - 5 dB.

For calculation of monopole source levels the arithmetic average of all propagation anomalies is added to the radiated noise levels of the limit curves, see Figure A. 26 and Figure A. 27. This procedure is applied in the range below 2 kHz where influence from Lloyd mirror can be expected. At higher frequencies the anomaly is assumed constant.

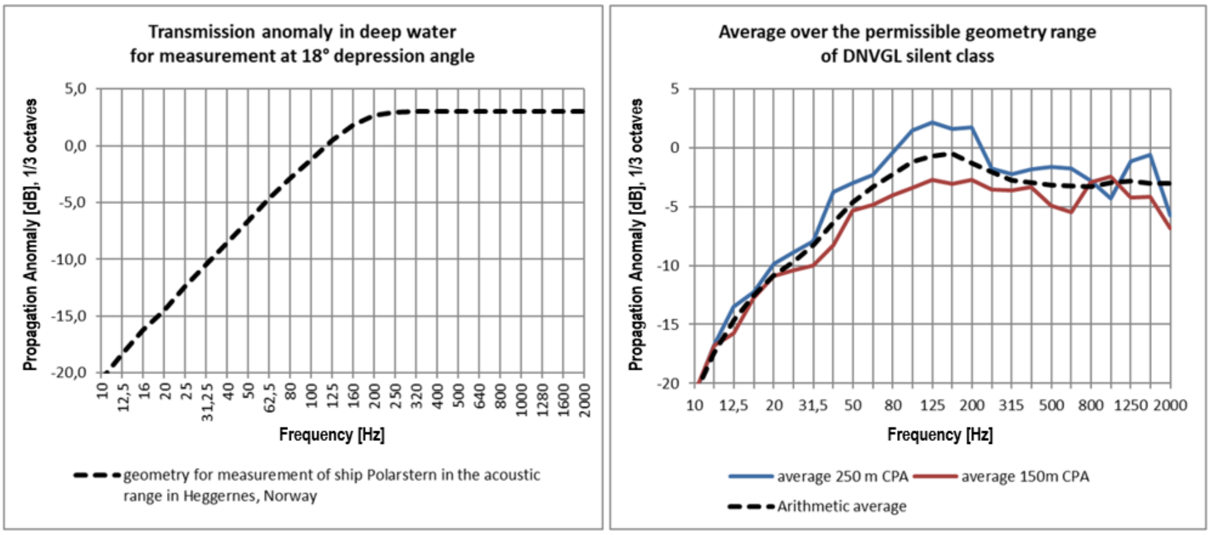
The reported RNL values of RV *Polarstern* were converted to MSL by the according transmission anomaly for deep water as shown on the right side of Figure A. 27.

Figure A. 26: Propagation anomaly for 150 m and 250 m closest approach distance, plotted for three different water depths 30 m, 65 m and 100 m.



Source: Author’s own.

Figure A. 27: **Left: Propagation anomaly of measurement geometry applied for ship Polarstern in deep water. Right: Average of all modelled propagation anomalies in the permissible range of the measurement geometry of DNVGL SILENT Class.**



Source: Author’s own.

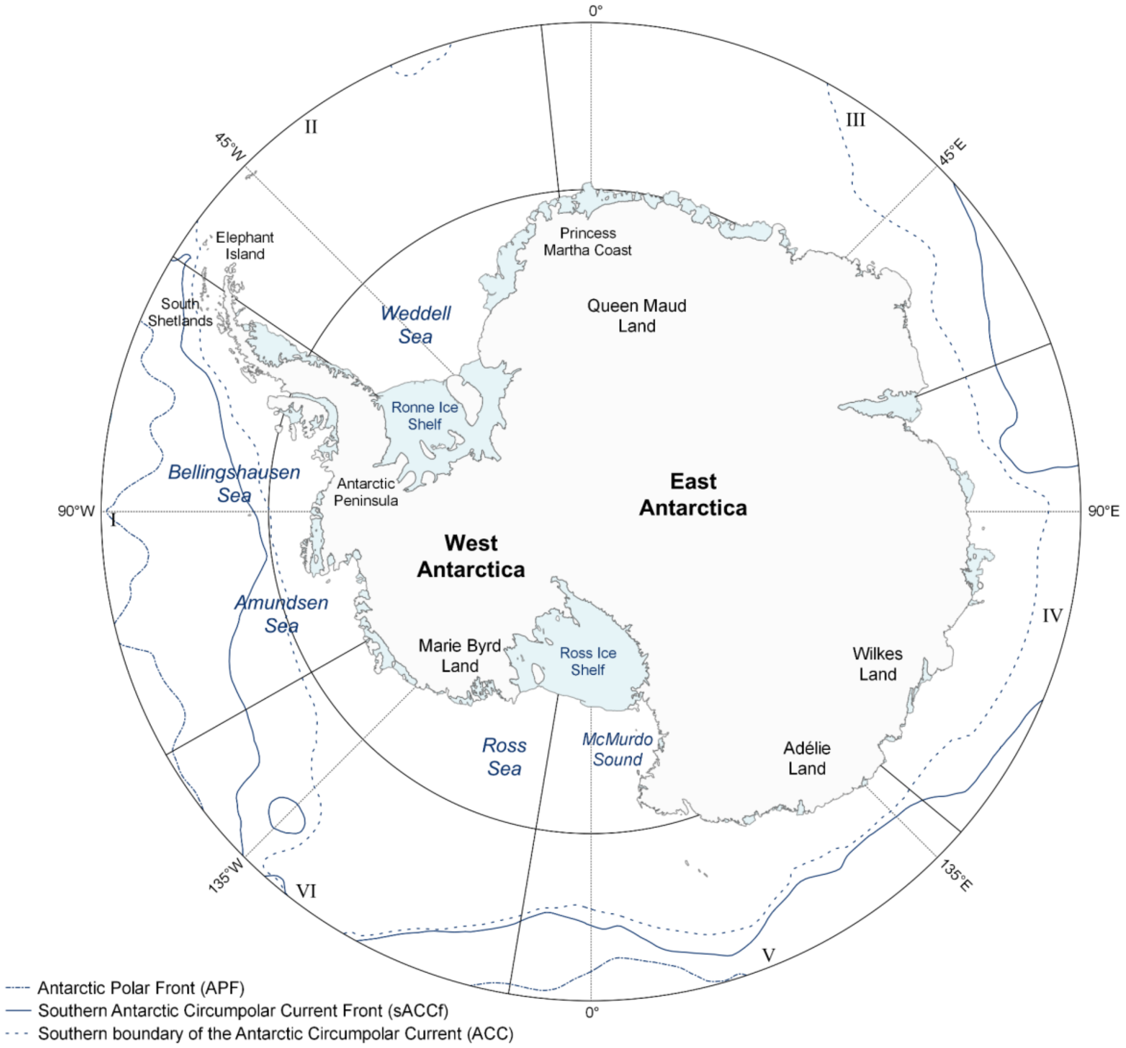
B Annex 2 - Investigating distribution and abundance of Antarctic marine mammals

Authors: Williams, R., Neilsen, K., Lo, C. Reiss, S. & Mendez-Bye, A.

B.1 Introduction

Anthropogenic noise poses a threat to marine mammals, particularly to species that rely on sound to communicate, navigate, and forage (Erbe et al., 2019). Mitigation against these impacts in the Antarctic requires knowledge of marine mammal distribution and abundance, which is lacking for most species south of 60°S. A review of best available information on spatial and temporal distribution and abundance will highlight data deficiencies and gaps, and facilitate discussions on mitigation measures against potential impacts of anthropogenic noise. Following similar bibliometric approaches (Williams et al., 2015; 2018), we conducted a literature review and summarized findings on spatio-temporal distribution and abundance of marine mammal species south of 60°S. This review includes preliminary analyses on available literature acquired from predetermined search words, as well as sightings available through open access databases and those shared directly by data providers. Inquiries were also sent to contact persons referenced on open access databases to account for potential surveys that were missing. The best available abundance estimates for each species are identified, and a review of space-use within the study area is provided. Lastly, knowledge gaps are highlighted to suggest areas for future research. Information from this review synthesizes existing knowledge of Antarctic marine mammals and will provide useful biological information for defining anthropogenic noise management metrics and mitigation strategies in the Southern Ocean.

Figure B. 1: Map of Antarctica, including waters south of 60°S. Ice shelves are shaded in light blue. Solid lines demarcate International Whaling Commission (IWC) management Areas I-VI, dashed lines represent longitude. Shapefiles for oceanographic fronts and currents were downloaded from Quantarctica; locations are estimated based on long-term temperature and salinity data (Orsi et al., 1995).



Source: Author's own.

B.2 Methods

B.2.1 Literature review/bibliometric analysis

Literature searches on Antarctic marine mammal abundance and distribution were conducted from December 2020 - February 2021 by querying Google Scholar with the search terms listed in Table B.1, in addition to using species-specific assessments from the International Union for Conservation of Nature (IUCN) Red List. A special emphasis was put on the inclusion of spatio-temporal studies that were not incorporated in a previous review related to the effect of anthropogenic noise on Antarctic marine mammals (Erbe et al., 2019). Reviews were conducted on available literature published in English, so while this analysis is broadly comprehensive, it is incomplete. Papers that returned final search terms were downloaded and stored in Elsevier, Mendeley Ltd. for analysis. Studies conducted north of 60°S, and those that did not include at least one of the target species (Table B. 1) were removed.

Table B. 1: Search terms used in Google Scholar.

Search Terms	Number of Papers
Antarctic marine mammal abundance	56
Antarctic marine mammal distribution	38
Antarctic marine mammal spatiotemporal	25
TOTAL	**119**

Shared datasets

The sightings data included were used to create species-specific distribution maps. Data were identified on open-source databases using the keywords and species names, or were acquired directly from authors during the literature search (Table B. 2, Data table Table B. 6). Where possible, we emailed points-of-contact for open-source databases and asked for information on any potential missing surveys. Raw data were filtered to retain only points south of 60°S. Datapoints were grouped by species and plotted in QGIS 3.10 (QGIS Development Team, 2020). Map aesthetics were chosen to ensure interpretability by simulating colour blindness and greyscale through preview mode in QGIS.

Table B. 2: Shared datasets containing information on marine mammal species found south of 60°S (Erbe et al., 2019).

Taxonomic Group	Scientific name	Common name	Database/owner
Phocid	*Ommatophoca rossii*	Ross seal	PANGAEA; OBIS-SEAMAP; GBIF; Tracey Rogers
Phocid	*Hydrurga leptonyx*	Leopard seal	OBIS-SEAMAP; MEOP; GBIF; Australian Antarctic Data Center; Tracey Rogers
Phocid	*Leptonychotes weddellii*	Weddell seal	OBIS-SEAMAP; MEOP; GBIF; Australian Antarctic Data Center
Phocid	*Lobodon carcinophaga*	Crabeater seal	MEOP; GBIF
Phocid	*Mirounga leonina*	Southern elephant seal	OBIS-SEAMAP; MEOP; GBIF
Otariid	*Arctocephalus gazella*	Antarctic fur seal	OBIS-SEAMAP; MEOP; GBIF
Mysticete	*Balaenoptera acutorostrata*	Common minke whale	PANGAEA; IWC; GBIF;OBIS-SEAMAP*

Taxonomic Group	Scientific name	Common name	Database/owner
Mysticete	*Balaenoptera bonaerensis*	Antarctic minke whale	PANGAEA; IWC*; OBIS-SEAMAP*; GBIF; Rob Williams
Mysticete	*Balaenoptera borealis*	Sei whale	PANGAEA; IWC; GBIF; Rob Williams
Mysticete	*Balaenoptera musculus brevicauda*	Pygmy blue whale	PANGAEA*; IWC*; OBIS-SEAMAP*; GBIF*
Mysticete	*Balaenoptera musculus intermedia*	Antarctic blue whale	PANGAEA*; IWC*; OBIS-SEAMAP*; GBIF*
Mysticete	*Balaenoptera physalus*	Fin whale	PANGAEA; IWC; OBIS-SEAMAP; GBIF; Rob Williams
Mysticete	*Eubalaena australis*	Southern right whale	PANGAEA; IWC; OBIS-SEAMAP; GBIF
Mysticete	*Megaptera novaeangliae*	Humpback whale	PANGAEA; IWC; OBIS-SEAMAP; GBIF; Rob Williams
Odontocete	*Berardius arnuxii*	Arnoux's beaked whale	PANGAEA; IWC*; OBIS-SEAMAP; GBIF
Odontocete	*Hyperoodon planifrons*	Southern bottlenose whale	PANGAEA; IWC*; OBIS-SEAMAP; GBIF; Rob Williams
Odontocete	*Mesoplodon grayi*	Gray's beaked whale	PANGAEA; IWC*; OBIS-SEAMAP
Odontocete	*Mesoplodon layardii*	Strap-toothed whale	PANGAEA; IWC*
Odontocete	*Ziphius cavirostris*	Cuvier's beaked whale	IWC*; OBIS-SEAMAP
Odontocete	*Mesoplodon europaeus*[5]	Gervais's beaked whale	GBIF
Odontocete	*Globicephala melas*	Long-finned pilot whale	PANGAEA; IWC; OBIS-SEAMAP; GBIF
Odontocete	*Lagenorhynchus cruciger*	Hourglass dolphin	PANGAEA; IWC; OBIS-SEAMAP; GBIF; Rob Williams
Odontocete	*Orcinus orca*	Killer whale (all ecotypes)	PANGAEA; IWC; OBIS-SEAMAP; GBIF; Rob Williams
Odontocete	*Phocoena dioptrica*	Spectacled porpoise	IWC
Odontocete	*Physeter macrocephalus*	Sperm whale	PANGAEA; IWC; OBIS-SEAMAP; GBIF

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[5] only one record for species and not included in the review

* Some species not distinguished in sightings data

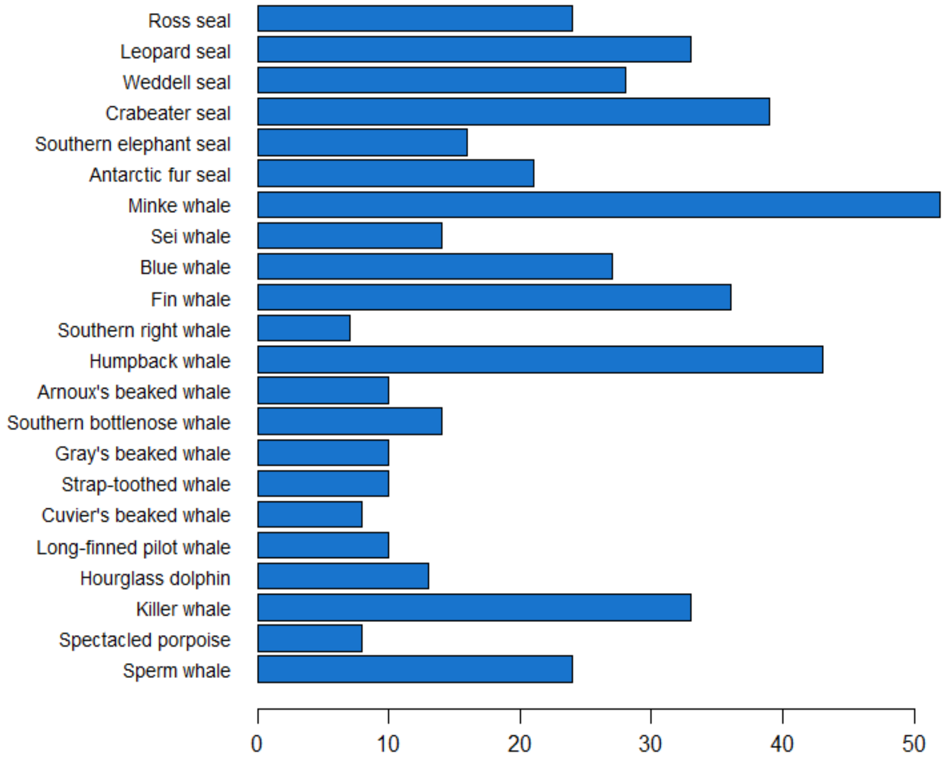
Taxonomic Group	Scientific name	Common name	Database/owner
Odontocete	*Tursiops truncatus*[6]	Common bottlenose dolphin	GBIF

B.3 Results

B.3.1 Bibliometric analysis

The selected key terms returned 142 papers (including 23 IUCN species assessments), but only 118 were focused on marine mammal distribution and abundance south of 60°S. An in-depth review of the literature and each of their reference lists added 73 papers that did not appear in the initial keyword search. Consultation with experts added 10 papers to the review that did not appear in the bibliometric search. The final 201 publications, covering all Antarctic marine mammal species (Figure B. 2), formed the foundation of this review, although not all contributed to the most relevant or current information summarized in Section B.2.1. The number of publications that included information on pinnipeds, mysticetes, and odontocetes by decade are summarized in Figure B. 3,Figure B. 4 and Figure B. 5.

Figure B. 2: Number of publications in literature review for each baleen whale, toothed whale, and pinniped species (n=201). Not all publications differentiated between Antarctic, common, and dwarf minke whales, or Antarctic and pygmy blue whales. These species are grouped as “minke whale” and “blue whale,” respectively.



Source: Author’s own.

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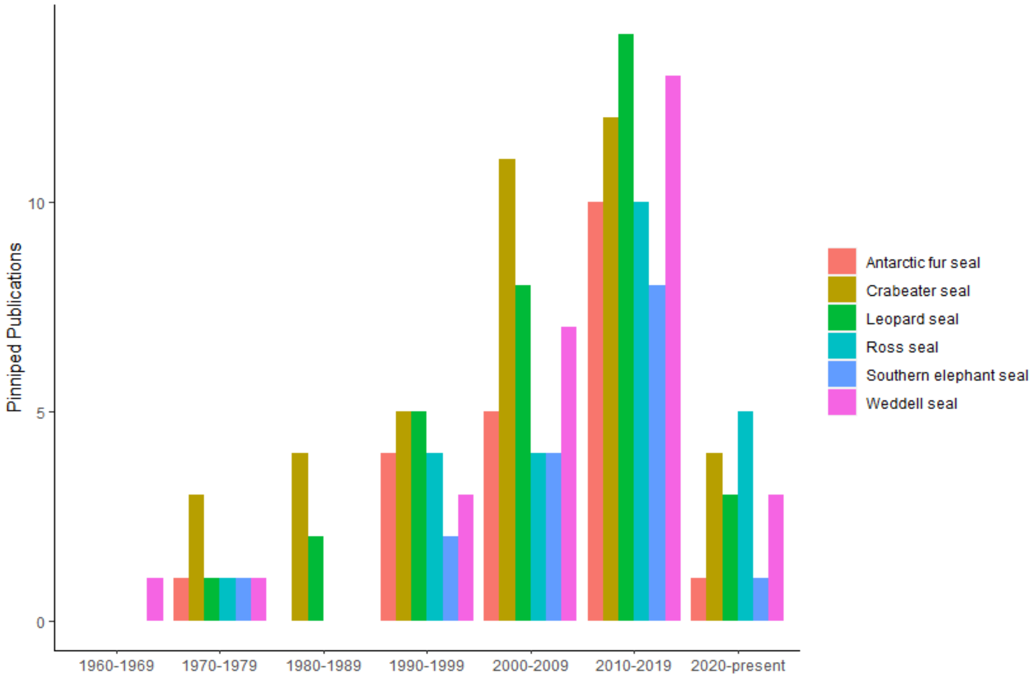
[6] only one record for species and not included in the review

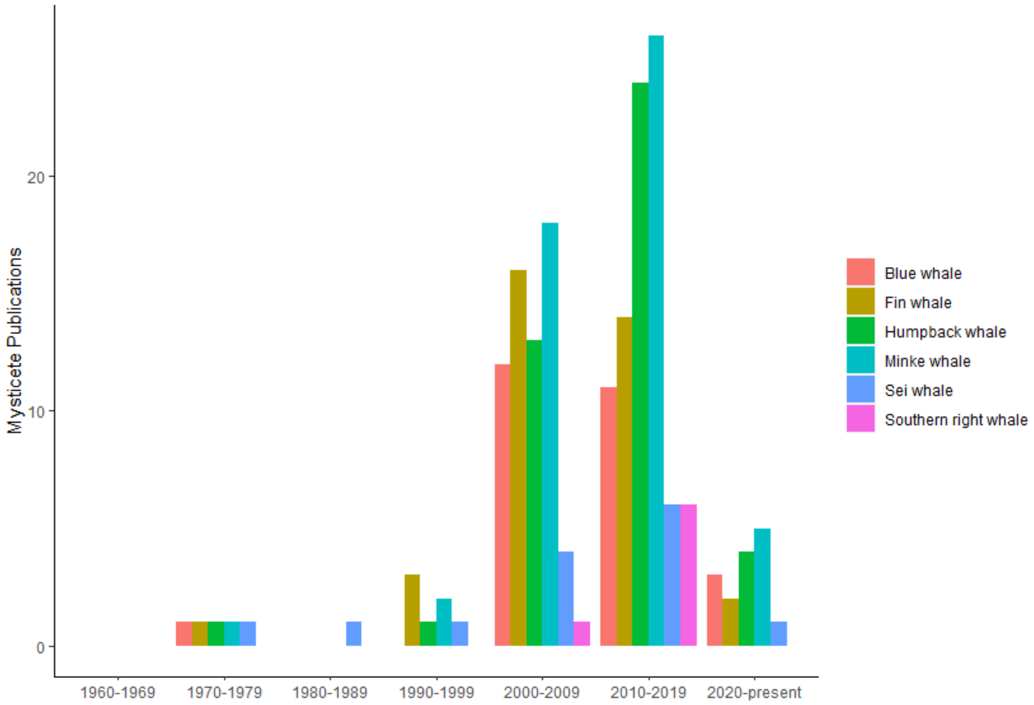
* Some species not distinguished in sightings data

Figure B. 3: **Number of publications for each Antarctic pinniped species by decade. Data rows are centered around the decade period.**



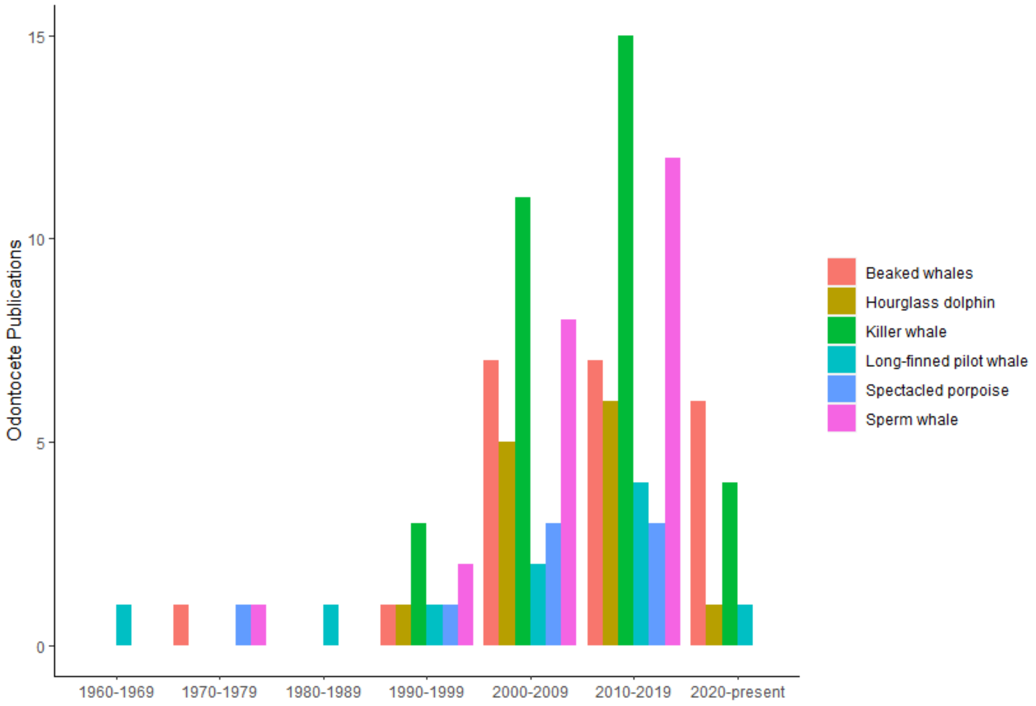
Source: Author’s own.

Figure B. 4: **Number of publications for each Antarctic mysticete species by decade. Data rows are centered around the decade period.**



Source: Author’s own.

Figure B. 5: Number of publications for each Antarctic odontocete species by decade. Data rows are centered around the decade period.

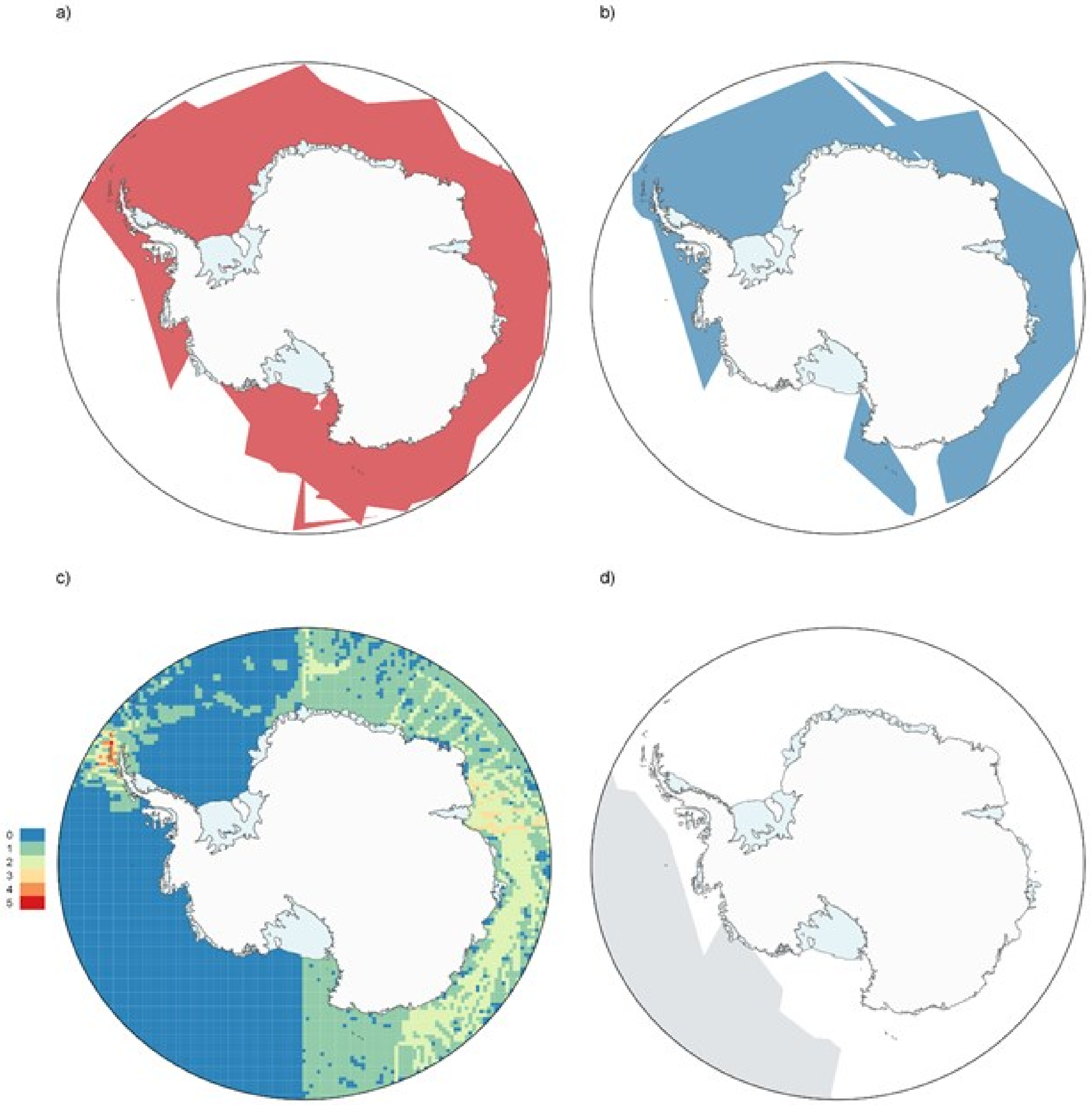


Source: Author’s own.

B.3.2 Antarctic marine mammal distribution and abundance

Marine mammals are widely distributed throughout the Antarctic south of 60°S. Spatial coverage of surveys was plotted to identify areas where research may be lacking (below). When track lines were unavailable, convex hulls of location-only data were created to illustrate relative search areas using the Minimum Bounding Geometry algorithm in QGIS. The available literature and shared datasets reveal well-supported spatial patterns and habitat preferences, as well as current estimates of abundance for some species throughout the study area. The species-specific distribution maps include tracking, sightings, acoustic presence, and catch data collected through a variety of methods (see Data table Table B. 6).

Figure B. 6: **Seasonal circumpolar distribution of survey effort for all included species based on the datasets available for this review. a) Illustrative study area in Antarctic summer months defined by convex hulls for presence-only data. b) Illustrative study area in fall, winter, and spring months (March-September) defined by convex hulls for presence-only data. c) Density of effort from line-transect surveys on a scale from 0 to 5 surveys per 500m^2 grid cell. Effort is limited to summer months. d) Polygon representing the region where survey effort data are especially lacking.**



Source: Author's own.

Pinnipeds

A systematic review of papers on spatio-temporal distribution and abundance of Antarctic phocids and an otariid south of 60°S are summarized. Data gaps as a result of outdated estimates or data deficiencies are identified (Table B. 3).

Table B. 3: Overview of Antarctic pinniped species south of 60°S.

Species	IUCN conservation status	Abundance estimates	Seasonality	Distribution	Dependencies	References
Ross seal	Least Concern	75,000[7]	Pack-ice associated in summer and pelagic in winter	Highest abundance 90-160°E and off EAP	Associate with dense pack-ice	Erickson & Hanson (1990); Blix & Nordøy (2007); Hückstädt (2015a)
Leopard seal	Least Concern	35,000	Pack-ice associated year-round; variability among individuals	Circumpolar	Associate with pack-ice	Rodgers et al. (2005); Hückstädt (2015b); Gurarie et al. (2017); Lowther (2018); Stainland et al. (2018)
Weddell seal	Least Concern	633,000	Some remain near continental breeding grounds year-round, some disperse to pack-ice	Circumpolar	Coastal fast-ice habitats	Stirling (1969); Siniff (1991); van Franeker (2002); Southwell et al. (2012); Ropert-Coudert et al. (2014); Hückstädt (2015c)
Crabeater seal	Least Concern	7,000,000- 15,000,000	Ice floes in winter, continental shelf and Antarctic slope front in summer	Circumpolar	Associated with pack ice, continental shelf, ice edge & floes; prey availability	Laws (1977, 1984); Ainley (1985); Erickson & Hanson (1990); Franeker (2002); Robinson et al. (2002); Ackley et al. (2003); Southwell et al. (2003); Siniff et al. (2008); Bengtson et al. (2011); Southwell et al. (2012); Hückstädt (2015d); Gurarie et al. (2017)

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[7] an outdated estimate

Species	IUCN conservation status	Abundance estimates	Seasonality	Distribution	Dependencies	References
Southern elephant seal	Least Concern	50,000[8]	Virtually found north of 60°S during winter; avoid persistent ice cover during spring and summer	Near circumpolar; migratory; reproduce in subantarctic	Retreating sea ice and increased temperature	van Franeker (2002); Siniff et al. (2008); Hofmeyer (2015); Raymond et al. (2015)
Antarctic fur seal	Least Concern	50,000[9]; 2,750,000[10]	Males travel south toward the WAP, females disperse from breeding grounds to ice-edge during winter; shallow waters and close to ice edge during autumn; open and deeper waters in spring	Migratory; breed on both subantarctic and Antarctic islands	Haul outs and breeding rookeries	Ribic et al. (1991); van Franeker (2002); Santora & Reiss (2011); Ropert-Coudert et al. (2014); Hofmeyr (2016); Lowther (2018)

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[8] Summer estimate

[9] Summer estimate

[10] Includes north of 60°S

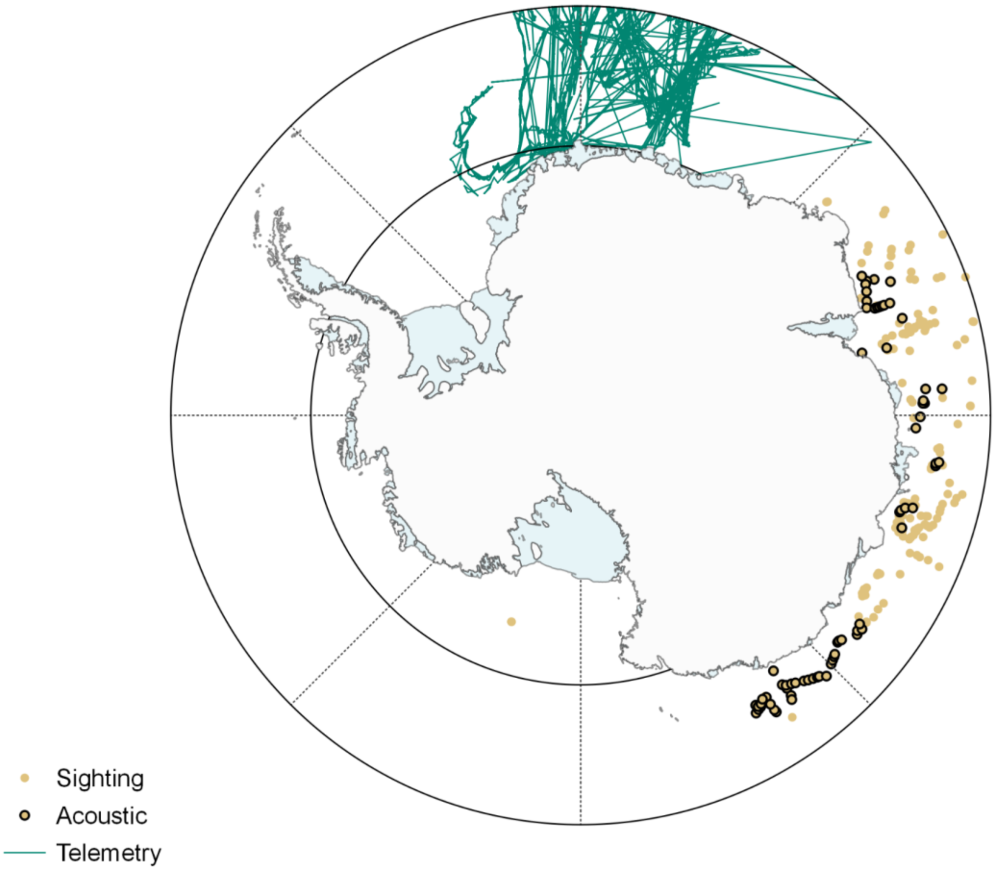
Ross seal

Ross seals have long been considered a rare species (Siniff, 1991; van Franeker, 2002), and their use of dense pack-ice habitat makes it difficult to obtain accurate abundance estimates (Bengtson et al., 2011). Circumpolar shipboard surveys between 1968 and 1983 produced a point estimate of 132,000 Ross seals (Erickson & Hanson,1990), which is consistent with research in heavy ice regions (van Franeker, 2002). Regional abundance in the Amundsen and Ross Seas is estimated to be 22,600 individuals (Bengtson et al., 2011). Antarctic Pack Ice Seal (APIS) surveys counted 78,500 animals (Southwell et al., 2012; Lowther, 2018). The IUCN reports a recent circumpolar estimate of 75,000 animals, but this number has also been considered outdated and unreliable (Hückstädt, 2015a). Circumpolar abundance of Ross seals south of 60°S remains unknown.

Visual surveys are the primary source of data on distributions given that very few individuals have been tracked. Data suggests that they can be found between the continental shelf and the southern portion of the Antarctic Circumpolar Current front (sACCf) (Ropert-Coudert et al., 2014). This species is likely distributed in open water during most of the year, and deep within the sea ice during spring pupping season starting in November (van Franeker, 2002; Blix & Nordøy, 2007). Acoustic occurrence of Ross seals in January is high close to the ice edge between 0-20°E and 60-130°E (Shabangu & Rogers, 2021). Erickson & Hanson (1990) found the lowest densities of Ross seals in the western Weddell Sea, and highest densities in the Pacific Sector (90-160°E) and the eastern Weddell Sea. A recent study using satellite tracking data in the eastern Weddell Sea and off Queen Maud Land showed that tagged individuals travelled northward to finish their annual molt and remained in the open ocean south of the Antarctic Polar Front (APF) (Wege et al., 2021). During the winter, they travelled toward the marginal ice zone (MIZ) within 500km of the ice edge, spending the majority of their time in the open ocean. Kernel density estimates showed that habitat-use was relatively the same in the summer and winter where they preferred to stay south of the APF in open ocean, and away from the continent. Suitable foraging habitat was predicted to be greatest during the summer compared to winter given their preference for open ocean (Wege et al., 2021).

Recent studies suggest Ross seals move into pack-ice by early October and stay until February before travelling north to forage in pelagic areas. They remain in open water south of the APF from February to October (Blix & Nordøy, 2007). In the Ross and Amundsen Seas, Ross seals concentrate in pack ice over deep water (Bengtson et al., 2011). In the eastern Weddell Sea, Ross seals are abundant off Queen Maud Land east of 30°W during summer and autumn, and are virtually absent in winter. They were not found in the innermost region past 73°S and generally were found east of 30°W (Bester et al., 2020). Off the Princess Martha Coast, Ross seal density was significantly correlated with total ice cover in late summer, and densities of seals on the pack ice increased through the season (Bester et al., 1995). A receding ice edge as a result of climate change is thought to be highly beneficial for Ross seals as that may reduce the energy expenditure needed to travel to suitable foraging habitats (Wege et al., 2021). However, since they rely on pack-ice to breed, an increase in competition with other pack-ice breeders could occur. Climate change induced alterations in their behaviour should be considered (Wege et al., 2021).

Figure B. 7: **Distribution of Ross seals (*Ommatophoca rossii*) south of 60°S from available sightings, acoustic presence, and tracking data. Solid lines demarcate 60 and 70°S and dashed lines represent longitude in 45° increments.**



Source: Author's own.

Leopard seal

An early abundance estimate for leopard seals south of 60°S was 300,000 animals (Erickson & Hanson, 1990). The IUCN Red List status of this species is 'Least Concern' and indicates the most recent estimate of 35,000 animals is likely very underestimated (Hückstädt, 2015b). Regionally, Gurarie et al. (2017) obtained an abundance estimate of 13,900 off Queen Maud Land and the eastern Weddell Sea (30°W-10°E). The Ross Sea population is estimated to be around 8,000 (Ainley, 1985), but when combined with the Amundsen Sea, the total for this region may be around 15,000 (Bengtson et al., 2011). Overall, abundance estimates for this species are uncertain and likely negatively biased given that a large proportion of individuals is pelagic and therefore not accounted for in haul-out studies (Southwell et al., 2012). Breeding females are the most frequently seen on ice floe haul-outs during the 7-week breeding period, although they often are not accompanied by other adults and the duration of the haul-out during the lactation period is unknown (Southwell et al., 2008).

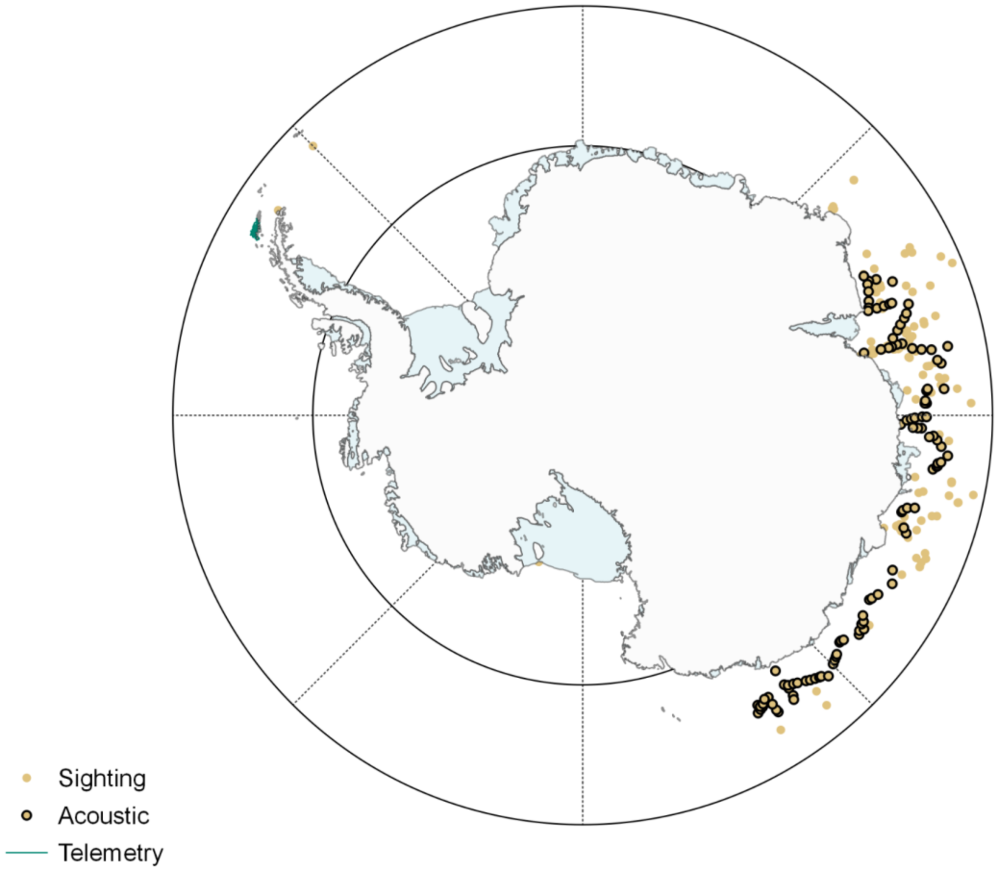
Leopard seals are year-round residents in the Antarctic with a circumpolar distribution, but they can also be found on subantarctic islands (Lowther, 2018). Individuals found farther north are thought to be immature (Siniff & Stone, 1985), and it has been shown that larger leopard seals, presumably of breeding age, are more widely distributed than smaller individuals (Rogers & Bryden, 1997). If the majority of sightings data are from younger individuals at higher latitudes, much of the available data are likely not representative of the adult population (Rogers et al., 2005). It is also important to note that this species is difficult to observe in visual surveys given its open water distribution (Southwell et al., 2008; Southwell et al., 2012). Little is actually known about the movement patterns and distribution of leopard seals (Siniff, 1991), though recent satellite tracking has provided some insight (Staniland et al., 2018).

It is known that leopard seals strongly associate with pack ice (Gurarie et al., 2017) where they give birth in the spring, and adult females have been shown to stay in this habitat year-round (Rodgers et al., 2005). Combined acoustic and tracking data suggest this species is very wide-ranging across pack-ice regions and throughout open water (Gedamke & Robinson, 2010; Shabangu & Rogers, 2021). They exploit a diverse range of habitats (Ropert-Coudert et al., 2014), being known to disperse to open water and ice-free coastal areas in winter (van Franeker, 2002; Nordøy & Blix, 2009). Densities of leopard seals are presumed highest at the pack-ice edge (Bester et al., 1995; Bester et al., 2002), but satellite tracking of adult leopard seals along the Western Antarctic Peninsula (WAP) in winter revealed no association with sea-ice edge (Meade et al., 2015). Distance to the coast was significantly related to sea-ice extent, with seals remaining closer to land when sea-ice extent was below 40% (Meade et al., 2015). Leopard seal home-range sizes increased as sea-ice area increased (Meade et al., 2015).

Leopard seals are less abundant in the Amundsen and Ross Seas, but during the months of December through March, the highest densities there were found in the northern pack ice over the continental shelf and within 100km of the ice edge (Bengtson et al., 2011). However, surveys conducted during summer months may have shown increased probability of occurrence near the ice edge possibly as a result of low ice coverage rather than a true association with proximity to the ice edge (Meade et al. 2015). Only one leopard seal was sighted on a ship-based cruise in the Ross Sea during late-autumn at about 73°S (Van Dam & Kooyman, 2004). Leopard seal acoustic detections in East Antarctica during January-February occurred exclusively in open water at or north of 62°S (Gedamke & Robinson, 2010). Acoustic data have indicated that leopard seal presence recorded in summer was highly predicted by month (Shabangu & Rogers, 2021). Acoustic presence of leopard seals around Elephant Island (South Shetland, WAP) is highly seasonal and increases in spring and early summer, likely in response to the breeding season (Meister, 2017). The summer population of leopard seals off the WAP is known to haul-out on land as opposed to ice (van Opzeeland & Hillebrand, 2020) in proximity to breeding colonies (Ropert-Coudert et al., 2014). In the pack-ice off Princess Martha Coast, seals were found near the retreating outer ice edge during December-February (Bester et al., 1995). In Admiralty Bay in the South Shetland Islands, seals can be found on the ice and in the water between September and November with peak abundance in October, though interannual variability of abundance is high (Salwicka & Rakusa-Suszczewski, 2002). A shipboard survey conducted in the pack ice of the northern Antarctic Peninsula in August 2012 reported 11 sightings of leopard seals indicating some individuals use this habitat in winter (Santora, 2014).

The north-south migration of this species has been observed in several studies over the last century (Southwell et al., 2012), and year-round satellite tracking has revealed northward movements in winter following the summer breeding season (Staniland et al., 2018). Rogers et al. (2005) found females farther south in the Antarctic, exhibiting finer-scale movements inconsistent with a northward winter migration. There is a lot of variability among individuals, so local populations likely have different movement and dispersion patterns (Rogers et al., 2005; Staniland et al., 2018).

Figure B. 8: Distribution of leopard seals (*Hydrurga leptonyx*) south of 60°S from available sightings, acoustic presence, and tracking data. Solid lines demarcate 60 and 70°S and dashed lines represent longitude in 45° increments.



Source: Author’s own.

Weddell seal

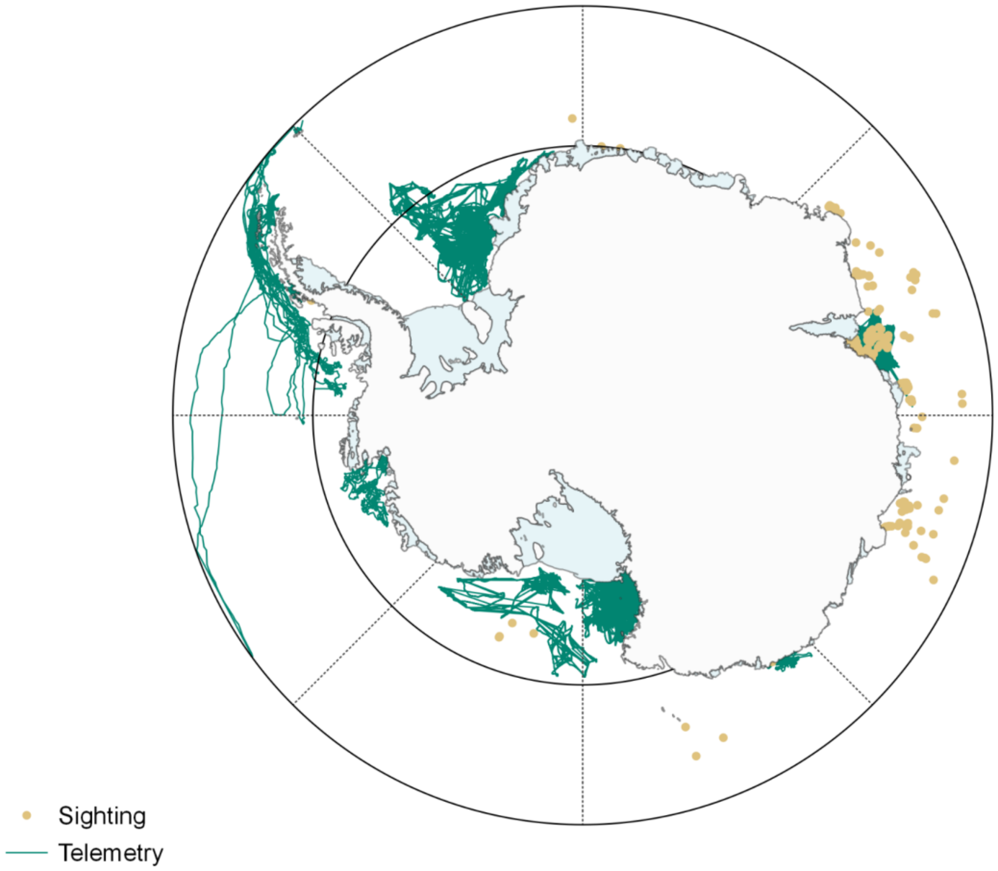
This species is designated as ‘Least Concern’ by the IUCN Red List (Hückstädt, 2015c) and the most recent and comprehensive abundance estimate of 633,000 individuals was based on surveys conducted between 150°E-100°W and 90°W-30°W during the APIS project from 1996-2001 (Southwell et al., 2012; Hückstädt, 2015c). Weddell seals are ice-seal residents and have a circumpolar and widespread distribution (van Franeker, 2002; Hückstädt, 2015c). They typically occupy nearshore fast-ice habitats by the Antarctic continent (Siniff, 1991). Weddell seals are coastal breeders that typically form colonies (e.g., McMurdo Sound) in early spring along cracks in fast ice and spend most of their time close to the Antarctic continent before dispersing more widely after birthing (Stirling, 1969; Siniff et al., 2008; Ropert-Coudert et al., 2014; Hückstädt, 2015c). Patterns of habitat-use on an individual scale appear to be variable; some remain close to colonies year-round and others move into pack-ice areas (Hückstädt, 2015c). Weddell seals were previously observed from 1988 to 2000 in Admiralty Bay in the South Shetland Islands, however, numbers declined over a long-term scale (Salwicka & Rakusa-Suszczewski, 2002). They were observed throughout the study area and near glaciers during summer, and presence declined after February. Less time was spent inside the bay as those areas may be better suited for individuals that are not feeding, but are undergoing breeding and molting seasons (Salwicka & Rakusa-Suszczewski, 2002). Interestingly, year-round passive acoustic monitoring at a recording site near the WAP showed a lower abundance, while a site further southeast around 68°S in the Weddell Sea revealed the greatest relative abundance in 2010 (van Opzeeland & Hillebrand, 2020).

Aerial surveys off Princess Martha Coast from December 1991 to February 1992 rarely encountered Weddell seals, likely due to these surveys being confined to pack-ice areas. Of the three individuals observed, they were closely associated with inshore fast ice (Bester et al., 1995). Similarly, only one Weddell seal was observed during a two-week winter survey around the South Shetland Islands and Elephant Island in August 2012 despite surveying pack ice (Santora, 2014). Cruise-based surveys to Port Foster, Deception Island in the South Shetland Islands from March 1999 to November 2000 found Weddell seals exclusively in November and they were evenly distributed around the shoreline (Kendall et al., 2003). Most were found hauled out at Telefon Bay and Whaler’s Bay. Sightings at Deception Island in November may be attributed to the residual ice coverage that was present in this area (Kendall et al., 2003).

Cruises during May of 1998 from Cape Washington and the Ross Sea only had two sightings of Weddell seals, at 69°S and at 75°S, likely because adult seals tend to be under coastal fast ice and juveniles tend to disperse into pack ice (Van Dam & Kooyman., 2004). Satellite images from March-October revealed Weddell seals use the continental slope and shelf in the Ross Sea (Ballard et al., 2012). This corroborates studies from surveys off Queen Maud Land in the Weddell Sea from 1996–97 and 2000-01 where they found seals both on and off the continental shelf (Gurarie et al., 2017), and telemetry data in the East Antarctica showing post-breeding females use shallow shelf waters near fast ice (Raymond et al., 2015). Line transect surveys in the Ross and Amundsen Seas during December 1999 to March 2000 found Weddell seals occurred primarily in fast-ice habitats (Bengston et al., 2011). Fewer seals were found in pack ice, although densities within the pack ice were greatest at depths ≤3000m and near fast ice (Bengston et al., 2011). Abundance in Ross and Amundsen Seas was estimated to be 330,000 individuals, and the highest densities were located between 180°W and 126°W (Bengston et al., 2011). Given that not all surveys extend into fast-ice habitats where densities of Weddell seals are known to be highest, abundances are likely underestimated and comparisons between them are complex (Bengtson et al., 2011).

More research investigating patterns of behaviour and habitat-use are important for estimating abundance under changing environmental conditions (Hadley et al., 2007; Siniff et al., 2008). Changes in sea-ice extent and thickness may impact tide-crack access for adults during the breeding season and affect pupping rates as a result of reduced foraging success in pregnant females. In order to produce comprehensive assessments and estimates of abundance for this species, future efforts conducting surveys in both pack-ice and fast-ice habitats will be crucial.

Figure B. 9: Distribution of Weddell seals (*Leptonychotes weddellii*) south of 60°S from available sighting and tracking data. Solid lines demarcate 60 and 70°S and dashed lines represent longitude in 45° increments.



Source: Author's own.

Crabeater seal

Crabeater seals are thought to be the most abundant marine mammal species in the world and are listed as 'Least Concern' by the IUCN Red List (Hückstädt, 2015d). Their estimated circumpolar abundance is between a minimum of 7,000,000 and a maximum of 15,000,000 individuals (Laws, 1977, 1984; Erickson & Hanson, 1990; Franeker, 2002; Bengtson et al., 2011; Southwell et al., 2012; Gurarie et al., 2017). The majority of crabeater seals are distributed in Antarctic waters, preferentially in sea-ice habitat (Franeker, 2002). Crabeater seals are commonly found on pack ice, near the continental shelf, and near ice edges (Bengtson et al., 2011), habitats that make them difficult to track and study (Ropert-Coudert et al., 2020).

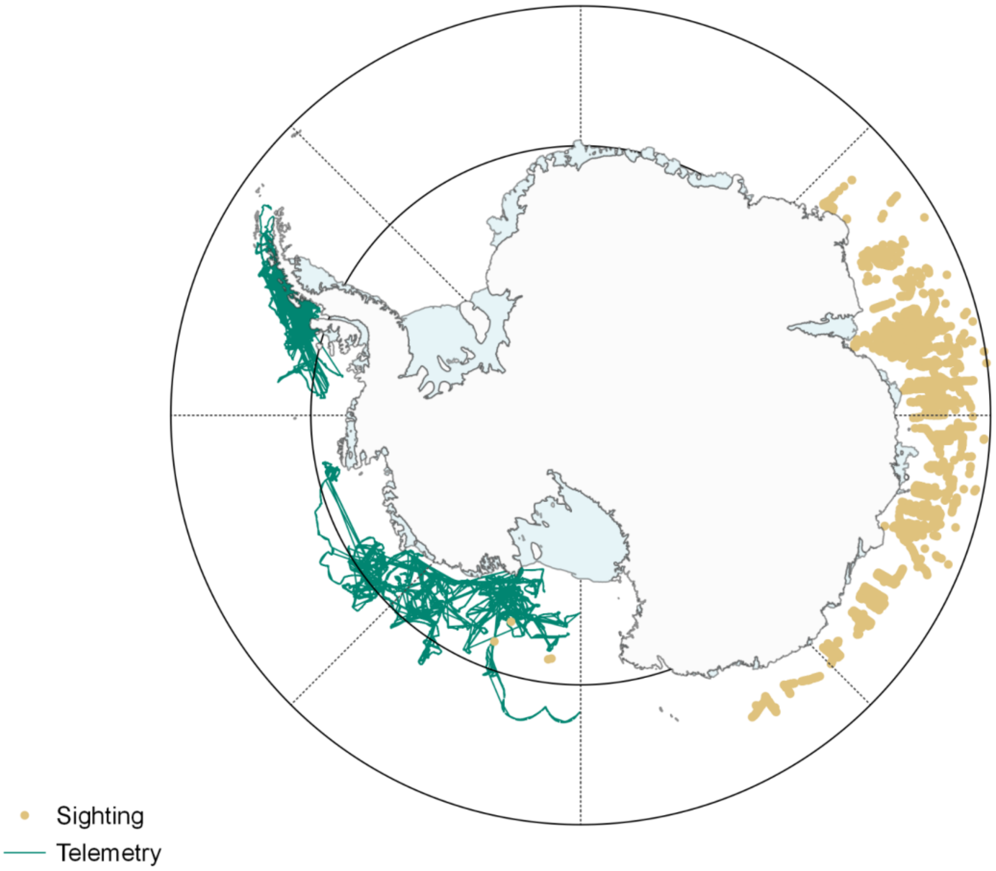
Cruises conducted during the late 1970s to early 1980s estimated 203,700 individuals in the Ross Sea (Ainley, 2010). A research cruise through the Ross Sea from May to June 1998 had few sightings (13 individuals), with the most southerly at 73°S and most northerly at 69°S (Van Dam & Kooyman, 2004). More recently, aerial and ship-based surveys within the Admundsen and Ross Seas from December 1999 through March 2000 obtained an abundance estimate of approximately 1.7 million (Bengtson, 2011); much greater than that estimated from surveys in the late 1970s/80s. Highest density was observed on pack ice during the Palmer II and Polar Star III surveys (1.39 seals per km2 and 1.42 seals per km2, respectively) where approximately 8,727 individuals were sighted. On average the seals were concentrated near the ice edge or continental shelf (Bengtson, 2011). Highest densities were found in areas of 50 to 90% ice coverage (0.85 seals per km2) and lowest in 90 to 100% ice coverage (0.44 seals per km2) (Bengtson, 2011). The seals were most common along the northern edges and over the continental shelf which is presumed to be tied to higher krill density, biological productivity, and easy access to open water (Ackley et al., 2003; Bengtson, 2011). The highest densities in the Ross and Amundsen Seas were found at 65-70°S, 160-170°E and 60-65°S, 150-140°W (Bengtson, 2011). Estimated abundance between 180°W to 130°W and 160°E to 180°E was 0.64 million and 0.20 million, respectively (Bengtson, 2011). The APIS project conducted from December 1999 to January 2000 by standardized line transect surveys looked at a region of 1,500,000 km^2 off East Antarctica between 60-150°E and observed 1,597 individuals within 1,000m of the ship (Southwell et al., 2004). Similarly, Princess Martha Coast aerial and ship surveys took place at the edge of fast ice at 70.19°S, 02.26°W and found 1,437 seals, of which 94.4% were crabeater seals (Bester et al., 1995). During December the inner pack ice had a relatively low density (0.56 seals per km2), as compared to the higher late season density of 1.17 seals per km^2 throughout the pack ice (Bester et al., 1995).

Crabeater seal density in Queen Maud Land was found to be approximately 14,000 seals per degree longitude (the highest density reported in the eastern Weddell Sea was 27.46 seals per nm2) with an estimated abundance of 7 million individuals (Gurarie et al., 2017). Predicted abundance of individuals along Queen Maud Land between 1999-2000 was approximately 515,000 individuals (Gurarie et al., 2017). The overall high densities recorded in the eastern Weddell Sea are thought to be a consequence of drastically reduced ice cover (Bester & Odendaal, 2000).

Acoustic detection of crabeater seals also indicate presence of this species south of 60°S. Crabeater seals were recorded acoustically from January to November 2013 at 65° 58.09’ S, 12° 15.12’ W (Hots, 2019). In the summer, seals were acoustically present 32.5% of the season (Hots, 2019). Presence increased significantly across the study from 1.5% in July to 100% in November (Hots, 2019). Crabeater seals have also been recorded acoustically off Elephant Island in the month of September for 2013, 2014, and 2015 and August only for the 2015 year (Meister, 2017).

Uncertainty surrounding haul-out preferences is evident and requires further research. For example, some studies found no evidence for ice floe preference (Bester et al., 1995), while others identified preferences related to ice floe size, concentration, and thickness (Condy, 1977; Bester et al., 2002; McMahon et al., 2002; Flores et al., 2008). Crabeater seals were exclusively recorded on deep pack ice in the southern Scotia (north of 60°S) and northern Weddell Seas during spring 1983, autumn 1986, and winter 1988 (Ribic et al., 1991). They have been found to associate with the interior of deep pack ice characterized by ice floes with a regular pattern and distribution (Ribic et al., 1991). Of the total 42 groups observed, group sizes ranged from 2 to 25 individuals, with 14 groups found in the open water and 28 groups on ice (Ribic et al., 1991). Studies have shown that the structure and size of ice floes are important to crabeater seals (Southwell et al., 2003). They breed on the ice and require larger, more stable floes than are available in the marginal ice zone (MIZ) (Siniff, 1981; Laws, 1984; Ribic et al., 1991). Mating and pupping season begins in early November (Southwell et al., 2003), and during this time of year females select ice floes that are both large and stable enough to occupy until the pup is weaned. Ice structure and size are important for protection from both predators and aggressive males, as well as providing an indirect influence on prey productivity (Siniff et al., 2008). Greater densities of crabeater seals have been reported near the continental shelf and Antarctic slope front in summer, coinciding with areas of high primary productivity (Ainley, 1985; Ackley et al., 2003; Southwell et al., 2012). Space-use is likely driven by the distribution of their prey, almost exclusively krill, which are often found in pelagic and slope areas and feed within 200m of the surface (Robinson et al. 2002; Siniff et al., 2008).

Figure B. 10: Distribution of crabeater seals (*Lobodon carcinophaga*) south of 60°S from available sighting and tracking data. Solid lines demarcate 60 and 70°S and dashed lines represent longitude in 45° increments.



Source: Author's own.

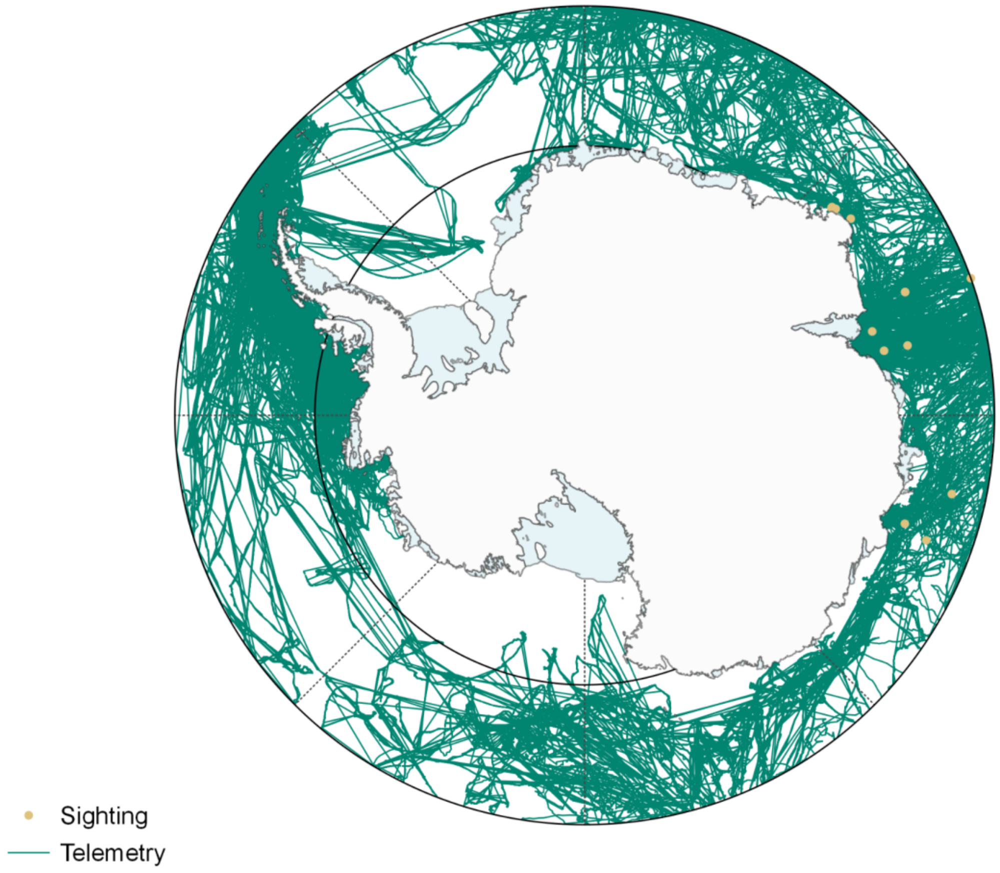
Southern elephant seal

Southern elephant seals are currently designated as 'Least Concern' by the IUCN Red List (Hofmeyr, 2015). These seals have a near circumpolar distribution and are a migratory, deep diving, land-breeding species that reproduce in subantarctic areas (van Franeker, 2002; Hofmeyr, 2015). Breeding grounds have been identified around the subantarctic islands near the APF, as well as the South Shetland and South Sandwich Islands before adults disperse to more southerly regions (Ropert-Coudert et al., 2014). During the winter, they are almost exclusively found north of 60°S and are occasionally hauled out on ice (van Franeker, 2002). However, males are known to occur along continental shores, likely using the continental shelf zone as a feeding habitat (van Franeker, 2002). Aside from a summer estimate of 50,000 individuals south of 60°S (van Franeker, 2002), a recent comprehensive estimate of abundance throughout their entire distribution has not been conducted (Hofmeyr, 2015).

Winter tracking of post-molting southern elephant seals from the South Shetland Islands observed seals close to the western part of the Antarctic Peninsula shelf, with some undergoing longer westward migrations to the APF or ice edge (Biuw et al., 2007; Ropert-Coudert et al., 2014). Those migrating east typically stayed north of the South Scotia Ridge (Biuw et al., 2007). Telemetry data during spring and summer in East Antarctica showed males and females avoided areas of persistent ice cover and concentrated in shallow parts of the continental shelf (Raymond et al., 2015). While Antarctic shelf waters are important habitats for both male and female southern elephant seals, tracking data from Conductivity-Temperature-Depth Satellite Relay Data Loggers (CTD-SRDL) showed females travelled northward when sea ice was advancing in late autumn and early winter, while males appeared to be less affected (Hindell et al., 2016; Treasure et al., 2017). Year-round monitoring of southern elephant seals showed no statistically significant difference in summer monthly averages between 1988-1995 and 1996-2000, concluding stable abundances on the western shore of Admiralty Inlet (South Shetland, WAP) (Salwicka & Rakusa-Suszczewski, 2002).

Although southern elephant seals are predicted to benefit from retreating sea ice as temperatures increase on the Antarctic Peninsula, it is uncertain how regional changes in climate may impact the food web and affect their populations (Siniff et al., 2008). At the current rate of climate change, range expansion may occur as more beaches in the Antarctic open up to opportunities for breeding, pupping, and molting. However, continued studies on their feeding and migratory patterns are required for future assessments (Bryden, 1993; Siniff et al., 2008).

Figure B. 11: Distribution of southern elephant seals (Mirounga leonina) south of 60°S from available sighting and tracking data. Solid lines demarcate 60 and 70°S and dashed lines represent longitude in 45° increments.



Source: Author’s own.

Antarctic fur seal

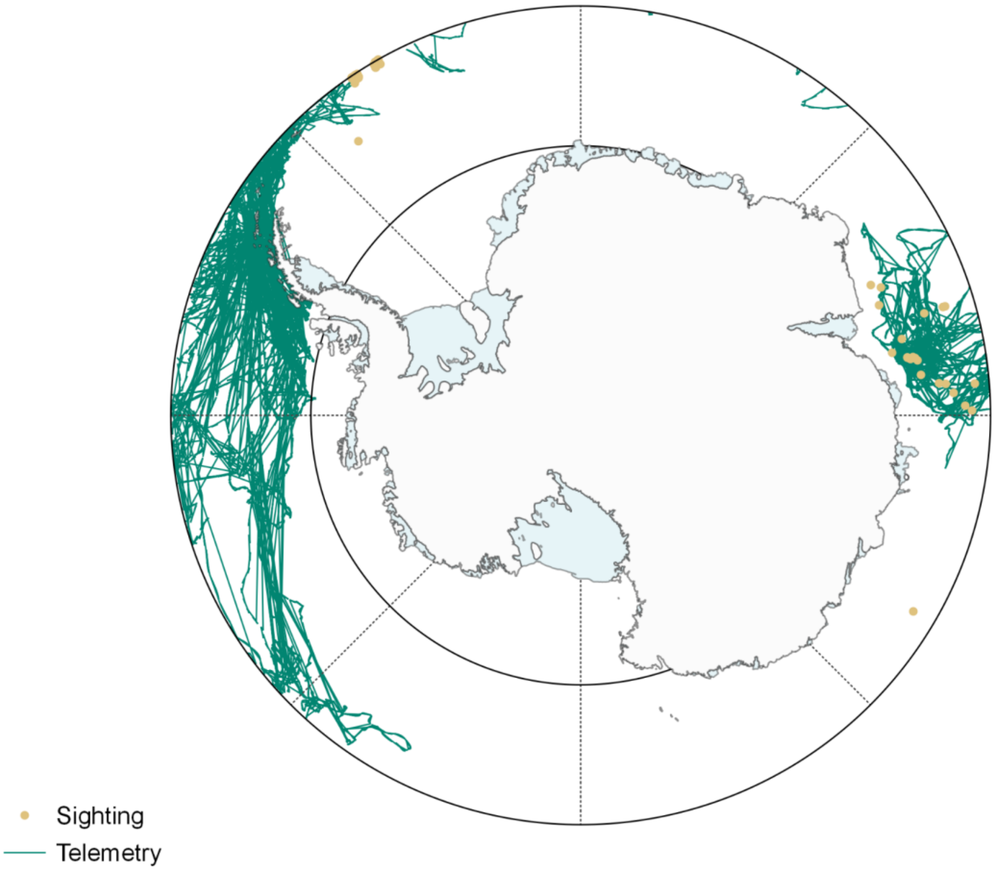
The IUCN Red List status of Antarctic fur seals is of 'Least Concern' (Hofmeyer, 2016). Abundance south of the APF is estimated around 2.75 million animals, though this number is thought to be closer to 50,000 animals south of 60°S during the summer breeding season (van Franeker, 2002). As of 2008, the abundance of Antarctic fur seals in February around Signy Island (South Orkney Islands) at 60°S in the northern region of the WAP was 12,607 (Waluda et al., 2010). Abundance in Admiralty Bay has shown to vary annually, but the overall trend revealed a high, short-term peak in abundance in March, and a lower yet longer peak between July and August (Salwicka & Rakusa-Suszczewski, 2002). Antarctic fur seal hotspots near the western half of Elephant Island and the Livingston and Seal Islets in Drake Passage (South Shetland, WAP) were also observed; abundance was negatively associated with distance from land (Santora & Veit, 2013). Abundance in Drake Passage is high during midsummer, but not as high as numbers in Bransfield Strait despite the absence of a breeding colony there (Bengtson et al., 1990; Santora, 2013).

Fur seals are not associated with the Antarctic Circumpolar Current (ACC), but rather concentrate within 100km of land (Santora, 2013). Two large breeding populations exist on Livingston Island and nearby islets of the South Shetland Islands (Santora & Reiss, 2011; Santora, 2013). These seals are abundant in the west submarine canyon where they tend to concentrate over the steep shelf-break along 500 and 1,000m isobaths, and inshore near 100m isobaths. This trend may reflect the migration between haul outs and breeding colonies on land (Santora & Reiss, 2011). The migration of these seals between breeding rookeries in South Georgia and the Antarctic Peninsula is well-accepted by researchers (Bengtson et al., 1990).

Antarctic fur seals breed on both subantarctic and Antarctic islands (van Franeker, 2002), and are associated with the Antarctic Peninsula (Ropert-Coudert et al., 2014). Female Antarctic fur seals forage in open water during winter and males are known to move south toward the WAP in this season (Lowther, 2018). In East Antarctica, important foraging habitat for adult males has been identified off Adélie Land (130-150°E). Foraging habitat for male Antarctic fur seals within the Antarctic may be characterized by reasonable proximity to subantarctic breeding grounds (Raymond et al., 2015). Kendall et al. (2003) found large numbers of fur seals around Port Foster (Deception Island, South Shetland) during February and March. Numbers in this area were lower during spring, though there was an overall increasing trend over the summer months. Bengtson et al. (1990) found absences of pups in previously described pupping areas in the South Shetland Islands, suggesting that newly established rookeries may be vulnerable to disturbance. The South Shetland Islands breeding population experienced dramatic growth through the 20th century (Hucke-Gaete et al., 2004).

Tracking data have suggested that females disperse widely from breeding grounds to the ice edge or APF during winter (Ropert-Coudert et al., 2014). Antarctic fur seals appear to be associated with the MIZ and cooler waters in the winter (Ribic et al., 1991). They distribute within broken pack ice in more inshore areas during this season (Whitehouse & Veit, 1994). In autumn, they are closest to the ice edge and can be found in more shallow waters, but do not show any significant association to ice (Ribic et al., 1991). In spring, they move farther away from the ice to open water and are found in deeper waters (Ribic et al., 1991). In the Weddell Sea during early spring, Joiris (1991) found seals concentrated on ice floes in the MIZ, with lower ice cover. Fur seals are increasingly being seen in open waters and along coasts south of the Bellingshausen Sea (van Franeker, 2002). This species may continue to expand its range southward given a likely reduction in krill availability in waters off breeding colonies, and increased availability of haul-out beaches with climate change-induced reductions in sea ice (Siniff et al., 2008).

Figure B. 12: **Distribution of Antarctic fur seals (Arctocephalus gazella) south of 60°S from available sighting and tracking data. Solid lines demarcate 60 and 70°S and dashed lines represent longitude in 45° increments.**



Source: Author’s own.

Cetaceans – Mysticetes

A systematic review of papers on spatio-temporal distribution and abundance of Antarctic mysticetes south of 60°S are summarized. Data gaps as a result of outdated estimates or data deficiencies are identified (Table B. 4).

Table B. 4: Overview of Antarctic mysticete species south of 60°S.

Species	IUCN conservation status	Abundance estimates	Seasonality	Distribution	Dependencies	References
Common minke whale	Least Concern	Data deficient	-	-	-	Cooke (2018a); Erbe et al. (2019)
Antarctic minke whale	Near Threatened	500,000	Some year-round; Associate with sea-ice cover in summer through winter	Circumpolar	Sea-ice; prey availability	Murase et al. (2002); Williams et al. (2006); Friedlaender et al. (2009); IWC (2013); Meister (2017); Cooke et al. (2018); Herr et al. (2019); Bassoi et al. (2020)
Sei whale	Endangered	Data deficient	-	Infrequent sightings south of 60°S	Feed within subantarctic; associated with warmer SST	IWC (1996); Ropert-Coudert et al. (2014); Cooke (2018b); Lowther (2018); Bassoi et al. (2020)
Pygmy blue whale	-	Data deficient	-	Some detection near edge of Antarctic continental shelf	-	Gedamke & Robinson (2010); Lowther (2018); Erbe et al. (2019)
Antarctic blue whale	Critically Endangered	2,280[11]	Summer circumpolar, however some males overwinter in feeding grounds; spring to summer	Circumpolar	Inter-annual movements associated with sea ice and deep continental slopes; prey distribution	Kasamatsu et al. (2000); Thiele et al. (2000); Murase et al. (2002); Širović et al. (2004); Branch (2007); Thomisch et

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[11] Summer estimate

Species	IUCN conservation status	Abundance estimates	Seasonality	Distribution	Dependencies	References
			follow marginal ice edge			al. (2016); Cooke (2018c); van Opzeeland & Hillebrand (2020)
Fin whale	Vulnerable	4,556	Year round migratory; far from ice edge, however congregate inshore during summer	Between 130°E-170°W and 70°E-130°E; deep shelf waters north of the Antarctic Peninsula	Currents, ice, bathymetry, prey distribution, and predator avoidance	Kasamatsu et al. (2000); Friedlaender et al. (2006); Matsuoka et al. (2006); Nicol et al. (2008); Orgeira et al. (2015); Cooke (2018d); Hots (2019); Bassoi et al. (2020)
Southern right whale	Least Concern	1,557[12]	Typically north of 60°S, summer occurrence in Subantarctic Front with some in the SW Atlantic and southern Indian Ocean	Summer abundance estimate within management Area IV (70°E-130°E)	Migrate based on breeding season	Matsuoka & Hakamada (2014); Ropert-Coudert et al. (2014); Cooke & Zerbini (2018)
Humpback whale	Least Concern	37,125	Migrate seasonally between breeding and feeding grounds (during summer); variable home ranges, may stay beyond summer	Circumpolar	Associated with feeding grounds, prey availability, and distance to shore in the WAP	Laws (1977); Matsuoka et al. (2005; 2011); Friedlaender et al. (2009); Ropert-Coudert et al. (2014); Curtice et al. (2015); Cooke (2018e); Schall et al. (2020)

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[12] Summer estimate

Minke whales

The IUCN Red List Antarctic minke whale status is listed as “Near Threatened” despite the population trend being unknown, and common minke whales are listed as “Least Concern” (Cooke, 2018a). Not all literature and datasets distinguished between dwarf (*Balaenoptera acutorostrata* (unnamed subspecies)), common (*B. acutorostrata*), and Antarctic minke whales (*B. bonaerensis*), so these were grouped (hereafter referred to as “minke whales”) unless specified otherwise. IDCR/SOWER (International Decade of Cetacean Research/Southern Ocean Whale and Ecosystem Research) survey estimates from the second and third circumpolar surveys were 747,000 and 461,000, respectively (Bravington & Hedley, 2009); Branch (2007) explored possible reasons for the decrease in estimates. The most commonly accepted abundance estimate for minke whales south of 60°S is 500,000 individuals, which is a 31% decrease from the previously accepted estimate of 760,000 individuals (IWC, 2013; Cooke et al., 2018).

There has been a lot of debate surrounding the variability in abundance estimates for this group of whales. Ainley (2010) indicated that minke whales likely exploited slope habitat after whaling of blue whales in the 1920s, and their numbers may have increased as a result of reduced intraspecific competition. However, Williams et al. (2014) found that the proportion of whales inside the ice could account for roughly half of the ~50% decline in abundance between late 1980s to 1990s IDCR/SOWER surveys in the Weddell Sea. A long-term abundance estimate based on DNA analyses indicated a population size of 670,000, suggesting that the actual abundance of this species, although uncertain, is likely around the same as the historical pre-whaling size (Ruegg et al., 2010). As minke whale occurrence is higher within areas of dense sea ice compared to open water (Ainley et al., 2007), some of the uncertainty around species abundance and population recovery status may be due to inaccessibility for data collection in this region.

Antarctic minke whales are a sea-ice dependent species and show high variability in density over space and time depending on ice concentration (Herr et al., 2019). They have been found to associate with dense sea ice in summer through winter (Ribic et al., 1991; Filun et al., 2020). They are generally distributed more closely to shore in cold deep water (Williams et al., 2006; Friedlaender et al., 2009; Bassoi et al., 2020) and near the ice edge in the summer (Kasamatsu et al., 2000; Williams et al., 2014), with peaks in January and February (Bombosch et al., 2014). More specifically, they have been found where the ice edge and the continental slope coincide (Murase et al., 2002), and in the winter they concentrate in ice-covered areas all along the continental shelf off the WAP (Thiele et al., 2004).

Minkes are most prevalent when the sea-ice cover is between 20 and 80% (Ribic et al., 1991; Ainley et al., 2012; Ainley et al., 2017). Acoustic data suggest that minke whale presence is linked to sea-ice (Meister 2017). Minke whales are present in the north WAP region near Elephant Island from June through September. Calls in this region declined during summer, but were still detectable, suggesting that some individuals remain in the area year-round (Meister, 2017). Other acoustic data reaffirm this finding, showing that calls increase from summer to winter and peak between June and November (Hots, 2019).

Although they are pagophilic, minke density in the Amundsen and Bellingshausen Seas near the WAP was inversely related to sea-ice concentration (Ainley et al., 2007). Distribution of minkes in this region shifted offshore in the MIZ once pack-ice waters froze and polynyas became less frequent (Ainley et al., 2007). In McMurdo Sound and around Ross Island in the Ross Sea, minke abundance was highest when ice cover decreased below 80%, but abundance decreased with ice cover below 30% (Ainley et al., 2017).

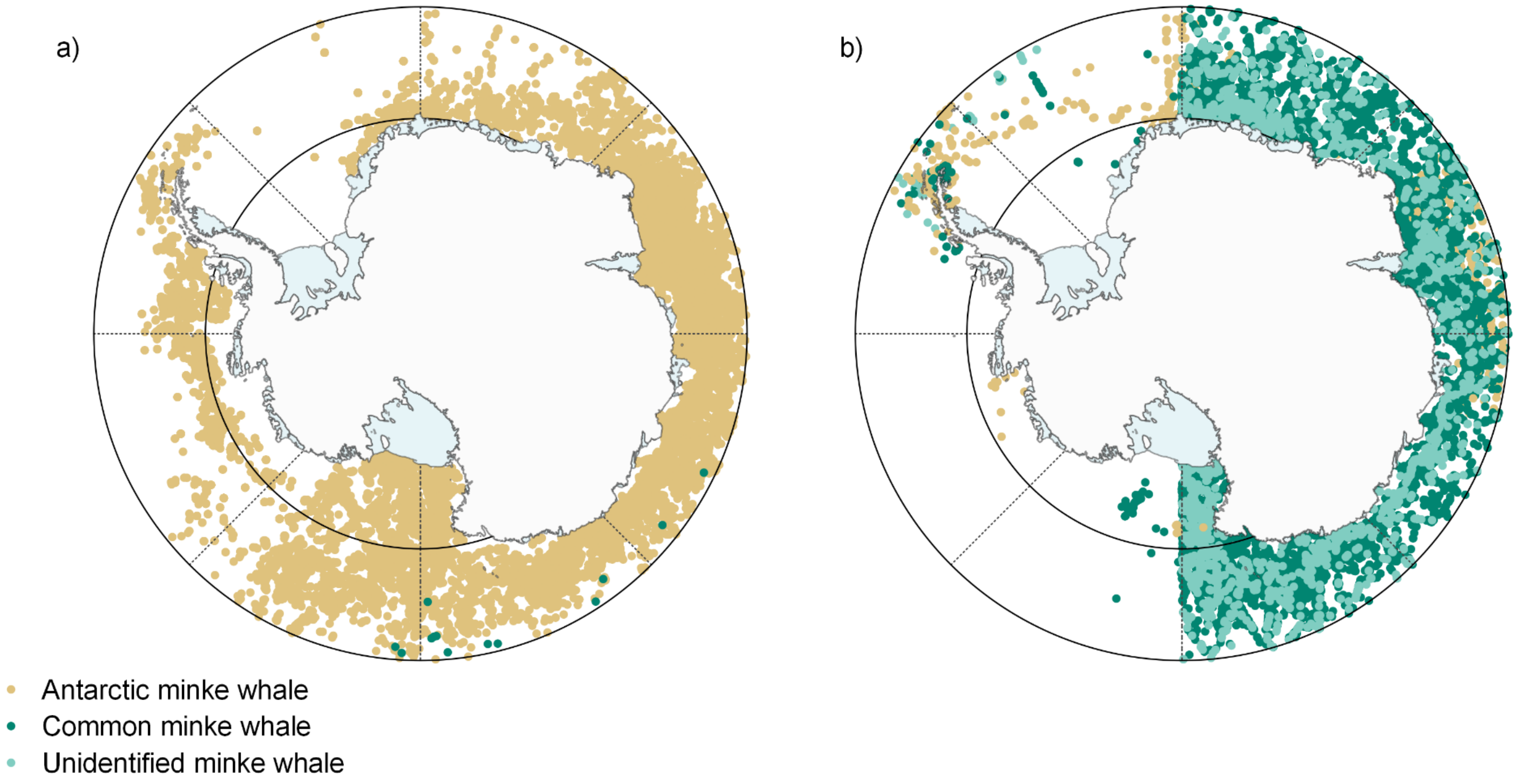
Exploratory analyses of aerial survey data suggested that minkes in the Weddell Sea are found in areas of modest sea-ice concentration ranging from 5-20% (Williams et al., 2011). Density was highest at the ice-edge boundary in this region (Williams et al., 2014). Approximately 20% of the minke whale population in the Weddell Sea could be within ice-covered regions of the MIZ and within pack-ice (Williams et al., 2014). Similarly, as much as 50% of the minke population along the eastern Antarctic Peninsula was estimated to have been within the sea-ice during a 2009/2010 summer survey (Kelly et al., 2014). Minke whale density was higher off the eastern Antarctic Peninsula than the ice-free waters of West Antarctica (Herr et al., 2019). Minkes concentrate south of the ACC and its southern boundary off the eastern Antarctic Peninsula, becoming less frequent farther offshore. Sightings in this region from summer surveys in 1995 and 1996 almost exclusively occurred with colder water along the Antarctic Coastal Current at the ice edge (Thiele et al., 2000).

Minke whales in the Antarctic have also been found to associate with dense aggregations of Antarctic krill, a main source of prey for this species (Murase et al., 2002). Minke whale concentration is higher where the ice edge extends over the continental shelf between 35°E and 145°W in summer months, coinciding with presence of Antarctic krill; minke whales were rarely seen offshore regardless of prey concentration (Murase et al., 2002). In the WAP, larger numbers of animals are likely to be found where ice margins intersect with prey availability (Thiele et al., 2004). In Marguerite Bay in the WAP region, minke whale relative abundance is linked with abundance and distribution of prey. Distribution in this region was associated with the sea-ice boundary and whales were not associated with areas far from the ice edge (Friedlaender et al., 2006). Minke whale presence in the Ross Sea follows a seasonal progression (Ainley et al., 2020). They are distributed closely along the MIZ as it first moves west, with a peak minke whale presence in mid-December, and then south into McMurdo Sound in the beginning of January (Ainley et al., 2020). These findings suggest a complex relationship between prey availability and sea-ice dependency for minke whale distribution.

During mid-summer, when the marginal ice edge is retreating and pack ice is consolidated, minke whales are thought to be spatially separated from other baleen whale species with respect to sea-ice proximity (Scheidat et al., 2011). Most minke whale sightings occurred further south and in or close to sea ice while other baleen species, including fin and humpback whales, were not found in ice-covered waters (Scheidat et al., 2011). Friedlaender et al. (2006) found that humpback and minke whales coincide with dense nearshore aggregations of krill during autumn, but avoid interspecific competition through vertical niche partitioning in the water column. Similar vertical niche partitioning has been observed between minkes and other mesopredators in the continental shelf and slope areas of this region (Ballard et al., 2012).

In the Ross Sea, krill abundance was found to decrease in the water column near the ice edge when Antarctic minke whales were present (Ainley et al., 2020). A behavioural avoidance response of Antarctic krill to the presence of a predator may increase competition pressure between multiple species utilizing the same prey source (Ainley et al., 2020). Although there is limited evidence to suggest minke whales experience interspecific competition with other baleen species, understanding the spatial and temporal variability in minke whale abundance and distribution is critical to evaluate their role in the recovery of other baleen whale species in the post-whaling era.

Figure B. 13: Distribution of minke whales (*Balaenoptera acutorostrata*, *Balaenoptera bonaerensis*) south of 60°S from a) catch data and b) available sighting data. Solid lines demarcate 60 and 70°S and dashed lines represent longitude in 45° increments.



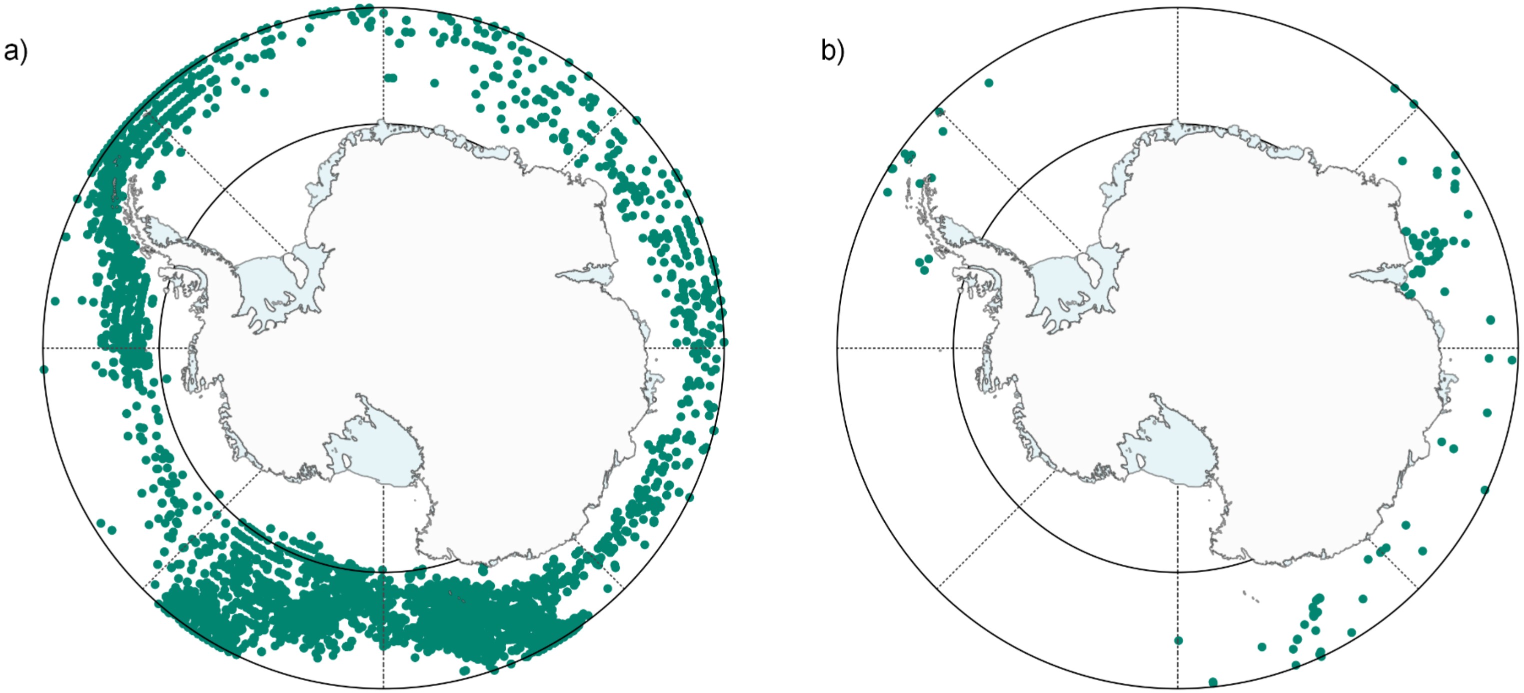
Source: Author’s own.

Sei whale

Historical evidence of continued decreased stock size in the 1960s and 1970s (Laws, 1977; IWC, 1980), and the lack of up-to-date surveys and abundance estimates results in this species remaining listed as 'Endangered' by the IUCN Red List (Cooke, 2018b). Based on IDCR and Japanese Scouting Vessel sightings data, the International Whaling Commission (IWC) estimated an abundance of 10,000 individuals south of 30°S in 1983 (IWC, 1996; Cooke, 2018b; Lowther, 2018).

Limited information on sei whale abundance and distribution, particularly south of 60°S, is available to date. This species typically feeds within the subantarctic as they are not krill specialists, and are rarely sighted south of 60°S (Ropert-Coudert et al., 2014). Recently, it was demonstrated that sea surface temperature played a role in the distribution of sei whales; there was a significant relationship between presence and warmer temperatures (Bassoi et al., 2020). While circumpolar distribution and abundance estimates were not identified from this review, opportunistic, although infrequent sightings have been recorded through various attempts to survey other marine mammal species. Sei whales were often encountered with fin whales offshore and in deeper abyssal waters (Scheidat et al., 2007; Bassoi et al., 2020). Acoustic detection of three likely sei whales were found along 64.51°-65.51°S (Gedamke & Robinson, 2010), with other visual sightings below 60°S ranging from as low as three positively identified individuals to 115 individuals (Thiele et al., 2000; Thiele et al., 2004; Scheidat et al., 2007; Bassoi et al., 2020).

Figure B. 14: **Distribution of sei whales (Balaenoptera borealis) south of 60°S from a) catch data and b) available sighting data. Solid lines demarcate 60 and 70°S and dashed lines represent longitude in 45° increments.**



Source: Author’s own.

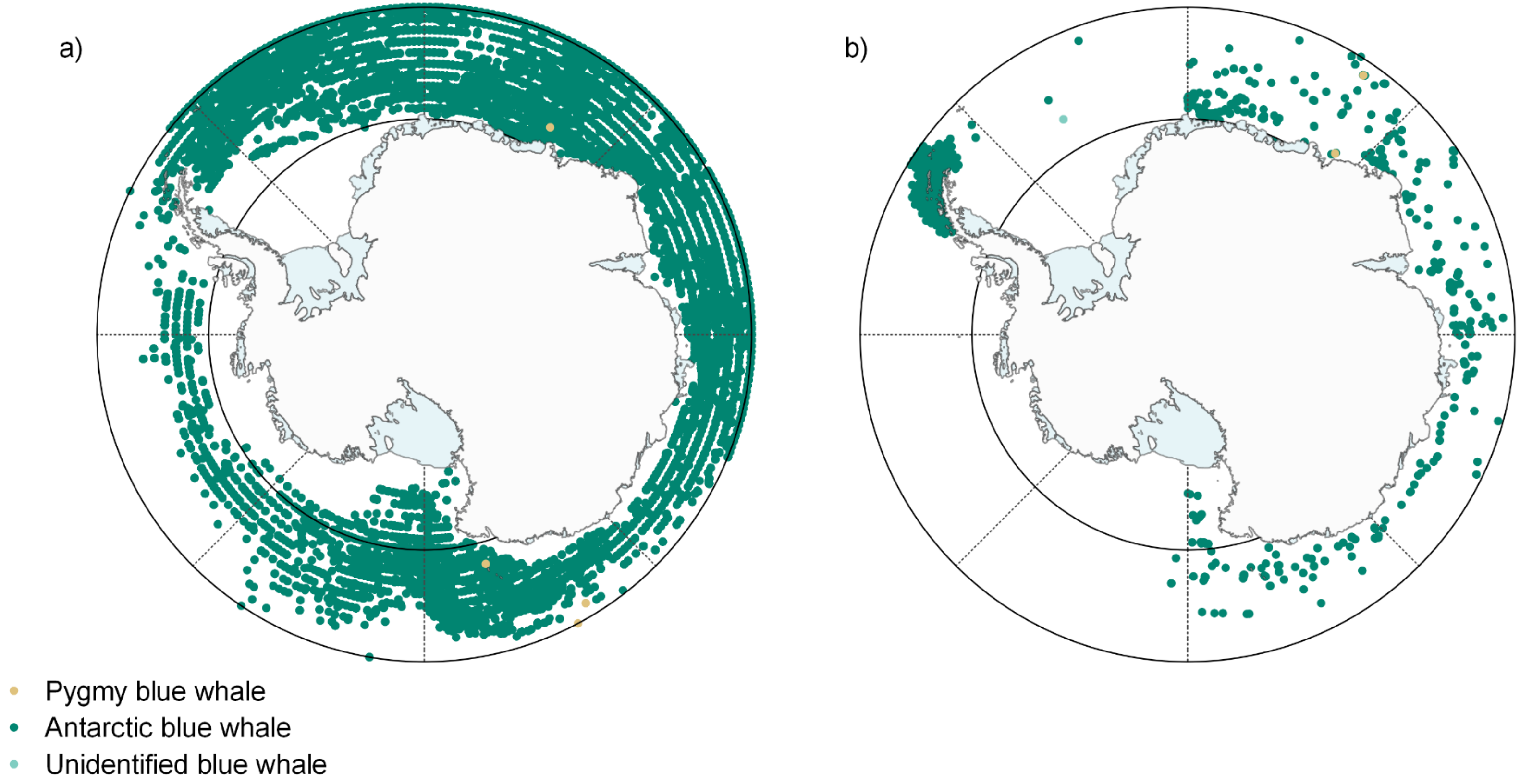
Blue whales

Previous research has identified blue whale sightings below 60°S as Antarctic blue whales (IWC, 2003; Branch, 2007). While pygmy blue whale sightings in this region are rare (Erbe et al., 2019), acoustic surveys have detected them at the edge of the Antarctic continental shelf, farther south than previously recorded (Gedamke & Robinson, 2010). Insufficient data exist to report on the abundance of pygmy blue whales in the study area (Lowther, 2018). For the purpose of this study, descriptions of blue whale distribution and abundance are focused on Antarctic blue whales.

Despite some population growth in recent years, Antarctic blue whales represent as little as 3% of their historical abundance as a result of intense whaling pressure. Analysis of mitochondrial DNA has revealed previously unsampled haplotypes that were used to estimate a post-whaling, or bottleneck, abundance of only 214 individuals (Branch and Jackson, 2008). As a result, the species is listed as 'Critically Endangered' on the IUCN Red List (Cooke, 2018c). The most recent circumpolar survey for Antarctic blue whales comes from the IDCR/SOWER surveys, estimating a summer abundance of 2,280 individuals south of 60°S (Branch, 2007). Regional abundance off the coast of Queen Maud Land was recently estimated to be 1,026 Antarctic blue whales between 0°E and 18°E (Paarman et al., 2021). This represents a higher density per 1,000km in this comparatively small area (24.63 individuals) (Paarman et al., 2021) than the circumpolar average from SOWER surveys (0.31-2.74 individuals per 1,000km) (Branch, 2007).

Antarctic blue whales have a circumpolar distribution during the summer, although passive acoustic surveys have identified characteristic Z-calls year round, suggesting that at least some individuals, likely males, overwinter at their Antarctic feeding grounds (Širović et al., 2004; Thomisch et al., 2016). Analysis of acoustic data collected during the IDCR/SOWER surveys revealed that summer call rates peaked in January and February (Shabangu et al., 2020). Biopsies taken during the IDCR/SOWER cruises and subsequent genetic analyses showed evidence for three sympatric populations that share feeding grounds in the winter, but likely have distinct breeding areas (Attard et al., 2016). Inter-annual movements have been explained by the formation and retreat of sea ice, with sightings generally concentrated along deep continental slopes (Kasamatsu et al., 2000). From spring to summer, Antarctic blue whales follow the MIZ where abiotic factors support enhanced primary productivity as the ice recedes (Thomisch, 2017; van Opzeeland & Hillebrand, 2020). Space-use is likely driven by the distribution of euphausiids (Thiele et al., 2000; Murase et al., 2002; Branch et al., 2007; Miller et al., 2019), although more research is needed to understand how blue whales, and other baleen whales, locate and target prey patches throughout the Southern Ocean.

Figure B. 15: **Distribution of blue whales (*Balaenoptera musculus brevicauda*, *Balaenoptera musculus intermedia*) south of 60°S from a) catch data and b) available sighting data. Solid lines demarcate 60 and 70°S and dashed lines represent longitude in 45° increments.**



Source: Author’s own.

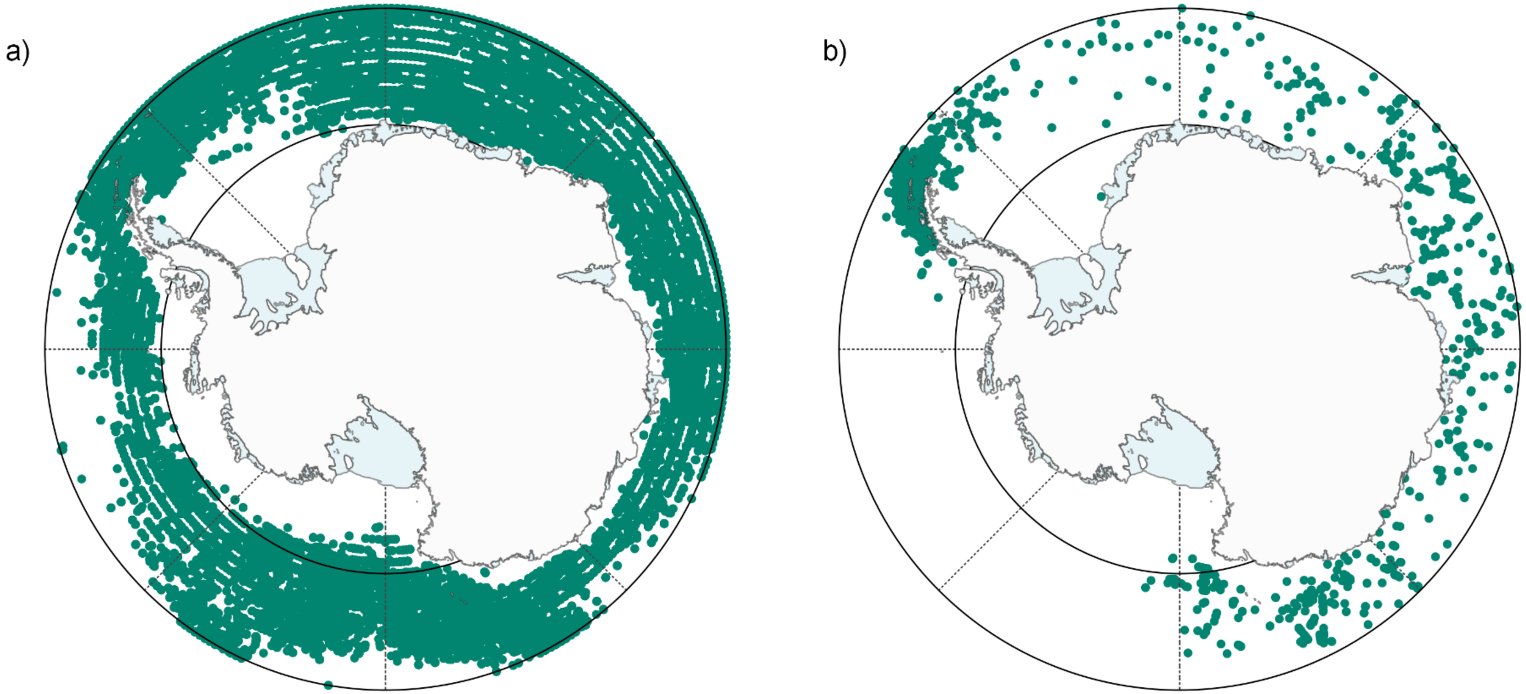
Fin whale

Fin whales are listed as 'Vulnerable' by the IUCN Red List (Cook, 2018d) with an estimated circumpolar abundance of 4,556 individuals south of 60°S (Matsuoka et al., 2006). Surveys in southern Drake Passage and Bransfield Strait observed 1,084 individuals and recorded the highest abundance between 60-62°S and 53-58°W (Santora & Veit, 2013). Increased abundance within these areas appear to be reflective of summertime conditions advantageous for replenishing energy reserves and breeding (Santora & Veit, 2013). Fin whale abundance in the southern Drake Passage was higher in areas where predicted densities of krill species T. macrura were highest, suggesting that fin whales aggregate in this region in the summer to feed (Herr et al., 2016). Predicted fin whale abundance in Drake Passage has been estimated at 4,898 individuals (0.117 whales per km^2) (Herr et al., 2016).

Research by the Institution of Cetacean Research found fin whales to be more abundant in areas south of 60°S between 130°E-170°W and south of 60°S between 70°E-130°E (Matsuoka et al., 2006). They tend to be farther from the ice edge during most seasons (Hots, 2019), however they are known to congregate inshore during summer (Tynan, 1998; Williams et al., 2014). Fin whales are commonly distributed in abyssal and deep shelf waters north of the Antarctic Peninsula (Bassoi et al., 2020). Continuous passive acoustic monitors deployed at five sites found the highest abundance of fin whales near the WAP (van Opzeeland & Hillebrand, 2020). Large fin whale aggregations are common along the WAP, likely due to high productivity in this area (van Opzeeland & Hillebrand, 2020), although further investigation is needed to better understand space-use in this region (Viquerat & Herr, 2017). Fin whales may prefer frontal areas (Tynan, 1998; Bost et al. 2009), and forage opportunistically on both krill and myctophid fish (Pakhomov et al., 1996; Hedley et al., 2001). They have been observed feeding on the largest mature krill (spawning stock), occurring continuously across the western waters of Drake Passage (Siegel et al., 2004; Bassoi et al., 2020). Fin whale distribution has been connected to a variety of variables, including currents, ice, bathymetry, and prey distribution, as well as predator avoidance and prey competition (Kasamatsu et al. 2000; Friedlaender et al. 2006; Nicol et al. 2008; Orgeira et al. 2015).

Although fin whales are a migratory species, they have been detected year-round in acoustic studies (Joiris & Dochy, 2013; Hots, 2019; Van Opzeeland & Hillebrand, 2020). Peaks in song associated with mating and feeding were solely produced by males during the winter (Hots, 2019), indicating that at least some individuals overwinter, and mating could take place before reaching higher latitudes (Hots, 2019).

Figure B. 16: **Distribution of fin whales (*Balaenoptera physalus*) south of 60°S from a) catch data and b) available sighting data. Solid lines demarcate 60 and 70°S and dashed lines represent longitude in 45° increments.**



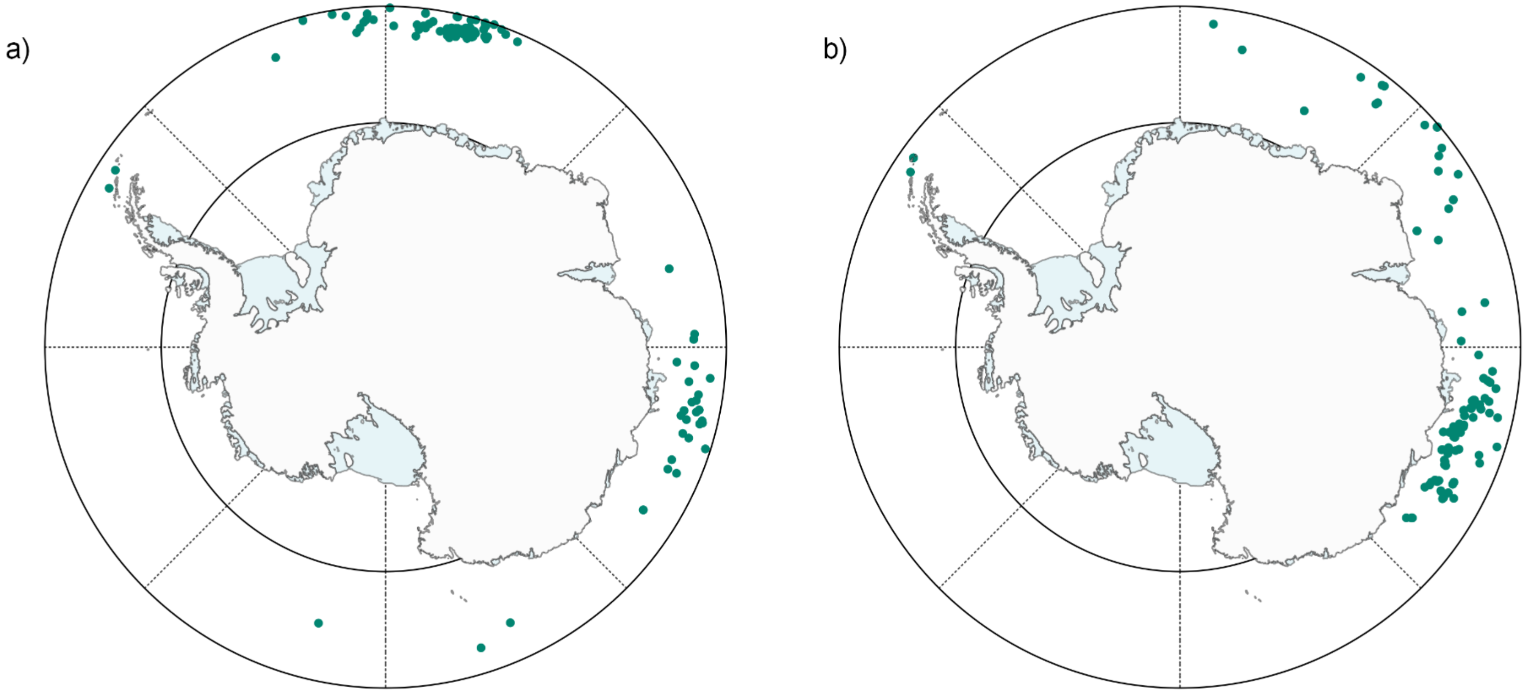
Source: Author’s own.

Southern right whale

Southern right whales were heavily exploited until the 1930s when legal protection was put in place (Matsuoka & Hakamada, 2014). Since then, recovery for this species has been steady and they have been designated as 'Least Concern' by the IUCN Red List (Cooke & Zerbini, 2018). The most recent population estimate south of 60°S comes from the JARPA (Japanese Whale Research Program under Special Permit in the Antarctic) and JARPAII 2007/2008 surveys, estimating a summer abundance of 1,557 individuals only within management Area IV (70°E-130°E) (Matsuoka & Hakamada, 2014).

Southern right whales historically move based on their breeding season where they are frequently found along the coastline of their northern range (Cooke & Zerbini, 2018). Previous studies demonstrate this species typically resides north of 60°S (Matsuoka & Hakamada, 2014; Lowther, 2018), with summer occurrence in the Subantarctic Front around 40-50°S in the southern Indian Ocean and South Atlantic. However, individuals have also been seen in the southwest Atlantic and southern Indian Ocean around 65°S (Ropert-Coudert et al., 2014). Although few studies have focused south of 60°S, repeated surveys from IWC/IDCR-SOWER cruises and JARPA and JARPAII have provided some information on distribution.

Figure B. 17: Distribution of southern right whales (*Eubalaena australis*) south of 60°S from a) catch data and b) available sighting data. Solid lines demarcate 60 and 70°S and dashed lines represent longitude in 45° increments.



Source: Author’s own.

Humpback whale

Humpback whales are currently classified as 'Least Concern' by the IUCN Red List (Cooke, 2018e), and this highly migratory species travels seasonally between breeding and circumpolar feeding grounds (Ropert-Coudert et al., 2014). Circumpolar distribution of humpback whales was largely identified through IWC/SOWER and JARPA surveys conducted south of 60°S. Humpbacks were widely distributed throughout IWC Areas IV and V (Matsuoka et al., 2005, 2011). Within Area V in particular, they were distributed along the Pacific Antarctic Ridge which marks the southern boundary of the ACC (Matsuoka et al., 2005). Transect surveys conducted between 63°S and the ice edge during the summer of 1995/1996 found all humpback sightings to be west of 120°E, with a wide latitudinal distribution. Conductivity, Temperature, and Depth (CTD) profiles also showed high integrated-Chlorophyll a was correlated with sightings, and were generally concentrated in areas south of the Antarctic Divergence and ACC (Thiele et al., 2000). Summer surveys across IWC Areas IV and V from 1980/1990-2004/2005 provided a combined abundance estimate of 37,125 individuals (Matsuoka et al., 2011). The IWC's multi-year assessment estimated the 2015 total population size within the Southern Ocean was 97,000 individuals (IWC, 2016; Cooke, 2018e).

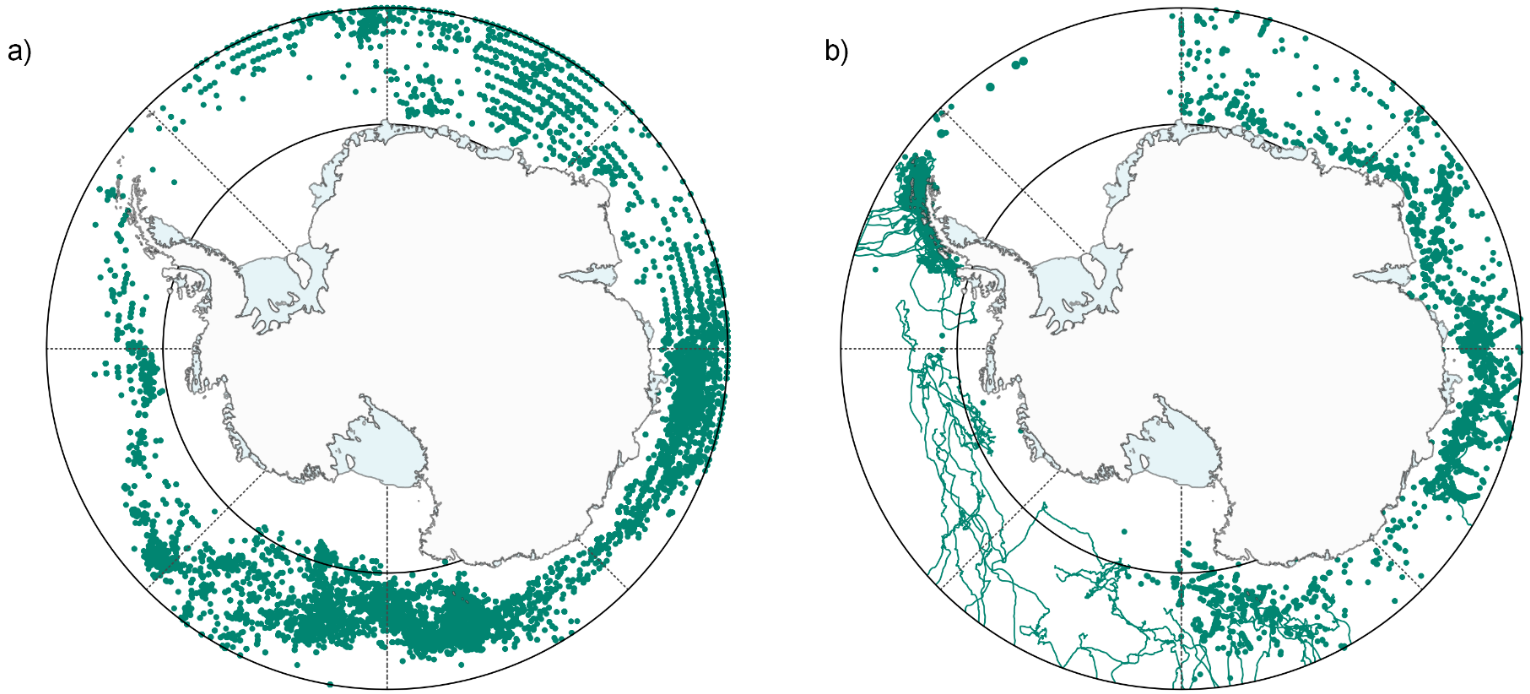
The humpback whale is one of the most abundant baleen whale species along the WAP (Thiele et al., 2004; Friedlaender et al., 2006). Considerable research has been done to relate oceanographic and environmental parameters and prey availability to Antarctic humpback whale distribution on a range of spatial and temporal scales. It is well documented that humpbacks migrate to Antarctic feeding grounds for the summer (Laws, 1977; Cooke, 2018e). Coastal distribution and hotspots have been found in the Bransfield Strait (Santora & Veit, 2013), Gerlache Strait (South Shetland, WAP), and along the coast of the Weddell Sea (Lazaneo et al., 2013), as well as high density areas near the South Shetland Islands (Scheidat et al., 2011). They have also been observed inshore and at depths less than 500m around Elephant Island (Scheidat et al., 2007). However, growing evidence from additional research has suggested that some individuals remain at Antarctic feeding grounds during the winter (van Franeker, 2002; van Opzeeland et al., 2013). For example, inshore waters including regions of Wilhelmina Bay, the Errera Channel, and Andvord Bay of the WAP were found to be important areas during autumn and early winter (Nowacek et al., 2011; Johnston et al., 2012). Austral autumn surveys on the distribution and abundance of humpback whales in Wilhelmina Bay and Andvord Bay revealed a density of 5.1 whales per km2 and 0.51 whales per km2 feeding on aggregations of krill, respectively (Nowacek et al., 2011). This corroborates sightings during the first joint Turkish–Ukrainian Antarctic Research Expedition in April of 2016 in the Lemaire Channel and Penola Strait (Öztürk et al., 2017).

Prior research on prey abundance and distribution related to humpback whales has shown whale space-use changes over the course of their feeding season (January to June) (Curtice et al., 2015). They have been associated with higher concentrations of prey and regions closer to shore in the WAP in autumn (Friedlaender et al., 2009), as well as during summer feeding months (March through June) (Curtice at al., 2015). Other efforts to identify relationships between whale species and prey availability have often combined krill predators (humpback whales and minkes; humpback whales and fin whales) in their analyses (Murase et al., 2002; Friedlaender et al., 2006; Herr et al., 2016). Large aggregations of euphausiids were correlated with krill predator distributions, and humpbacks were associated with the large aggregations regardless of topography (open water or continental slope). In particular, humpbacks were observed along 60°S, 100°E which had sea ice present a week prior to the survey, suggesting that high prey density could be related to the retreat of sea ice (Murase et al., 2002). Humpback and minke whales were strongly correlated with prey distribution in autumn around Marguerite Bay

(Friedlaender et al., 2006). Although the Friedlaender et al. (2006) study did not have the statistical power to look at interspecific relationships, other studies have provided support that humpbacks are significantly associated with sea ice and the seasonal MIZ (Thiele et al., 2004; Cotté & Guinet, 2011). Aerial surveys of humpback whales and fin whales conducted between austral summer and autumn along the Bransfield Strait and Drake Passage demonstrated horizontal niche partitioning (Herr et al., 2016). Humpback whales were associated with medium biomass of a particular krill species (E. superba) along the coastal areas of Bransfield Strait at an estimated density of 0.056 whales per km2. In contrast, fin whales were associated along the shelf edge of the South Shetland Islands of Drake Passage where there was a lower biomass of *E. superba*; the authors provided a density estimate of 0.117 whales per km2 (Herr et al., 2016). Although the authors from this study were able to evaluate predicted prey distributions, the small sample size limited their ability to build a distribution model. More krill data are needed to determine if size-dependency is a driver for humpback whale feeding behaviour and distribution (Herr et al., 2016).

Attempts to understand humpback distribution beyond summer have been supplemented by acoustic monitoring. In 2013, humpbacks were found at 9 recording sites throughout the Atlantic sector of the Southern Ocean (ASSO) during summer and autumn (January-June), demonstrating that the ASSO may serve as an important feeding ground for certain breeding stocks (IWC, 2011; Schall et al., 2020). Additionally, acoustic detection of humpbacks from the Perennial Acoustic Observatory (70°31'S, 8°13'W) in 2008/09 occurred throughout winter months (van Opzeeland et al., 2013). These studies demonstrate that humpback whale home ranges are seasonally variable, and that individuals could remain in these foraging grounds outside their peak feeding season (Curtice et al., 2015; Schall et al., 2020). Further research concerning extended presence in Antarctic waters beyond the summer season is necessary to understand their full migratory behaviour as environmental conditions change.

Figure B. 18: **Distribution of humpback whales (Megaptera novaeangliae) south of 60°S from a) catch data and b) available sighting and telemetry data. Solid lines demarcate 60 and 70°S and dashed lines represent longitude in 45° increments.**



Source: Author’s own.

Cetaceans - Odontocetes

A systematic review of papers on spatio-temporal distribution and abundance of Antarctic odontocetes south of 60°S are summarized. Data gaps as a result of outdated estimates or data deficiencies are identified (Table B. 5).

Table B. 5: Overview of Antarctic odontocete species south of 60°S.

Species	IUCN conservation status	Abundance estimates	Seasonality	Distribution	Dependencies	References
Beaked whales	Least Concern	Data deficient	-	Circumpolar; along the continental slope and between the ACC and ice edge; species-	Beaked whales	Least Concern
Long-finned pilot whale	Least Concern	Data deficient; 200,000[13]	Greatest encounter rates observed in mid-late January	Most remain north of the APF, but few found in the Bellingshausen Sea	-	Kasamatsu & Joyce (1995); van Franeker (2002); Minton et al. (2018)
Hourglass dolphin	Least Concern	10,000[14]; 144,300[15]	Increased presence during warmer SST from February to March	Circumpolar in open water near ACC, shelf-slope, and sea ice	Associate with warmer sea surface temperature	Kasamatsu & Joyce (1995); van Franeker (2002); Braulik (2018); Bassoi et al. (2020)
Killer whale (all ecotypes)	Data Deficient	24,790 - 91,310	Type A: pelagic in summer, winter distribution unknown; Type B: pack ice in summer, subtropical waters in winter; Type C: pack	Circumpolar; Type D in subantarctic and temperate waters north of 60°S	Movement across ecotypes are likely driven by prey	Gill & Thiele (1997); Branch & Butterworth (2001); Pitman & Ensor (2003); Van Dam & Kooyman (2004); van Waerebeek et al. (2010); Ballard et al. (2012); Durban &

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[13] Includes north of 60°S

[14] Summer estimate

[15] Includes north of 60°S

Species	IUCN conservation status	Abundance estimates	Seasonality	Distribution	Dependencies	References
			ice in summer, winter distribution unknown, possibly resident year-round			Pitman (2012); de Bruyn et al. (2013); Reeves et al. (2017)
Spectacled porpoise	Least Concern	Data deficient	-	Circumpolar	-	Baker (1977); Goodall & Schiavini (1995); Sekiguchi et al. (2006); Dellabianca et al. (2018); Erbe et al. (2019)
Sperm whale	Vulnerable	10,000 - 12,000	Migrate to lower latitude in winter and increase in the Antarctic during summer	Latitudinally segregated by size and sex; patchy	Far from ice edge and deep water; prey dependent	Kasamatsu et al. (2000); Branch & Butterworth (2001); van Franeker (2002); van Waerebeek et al. (2010); Ropert-Coudert et al. (2014); Meister (2017); Erbe et al. (2019); Taylor et al. (2019)

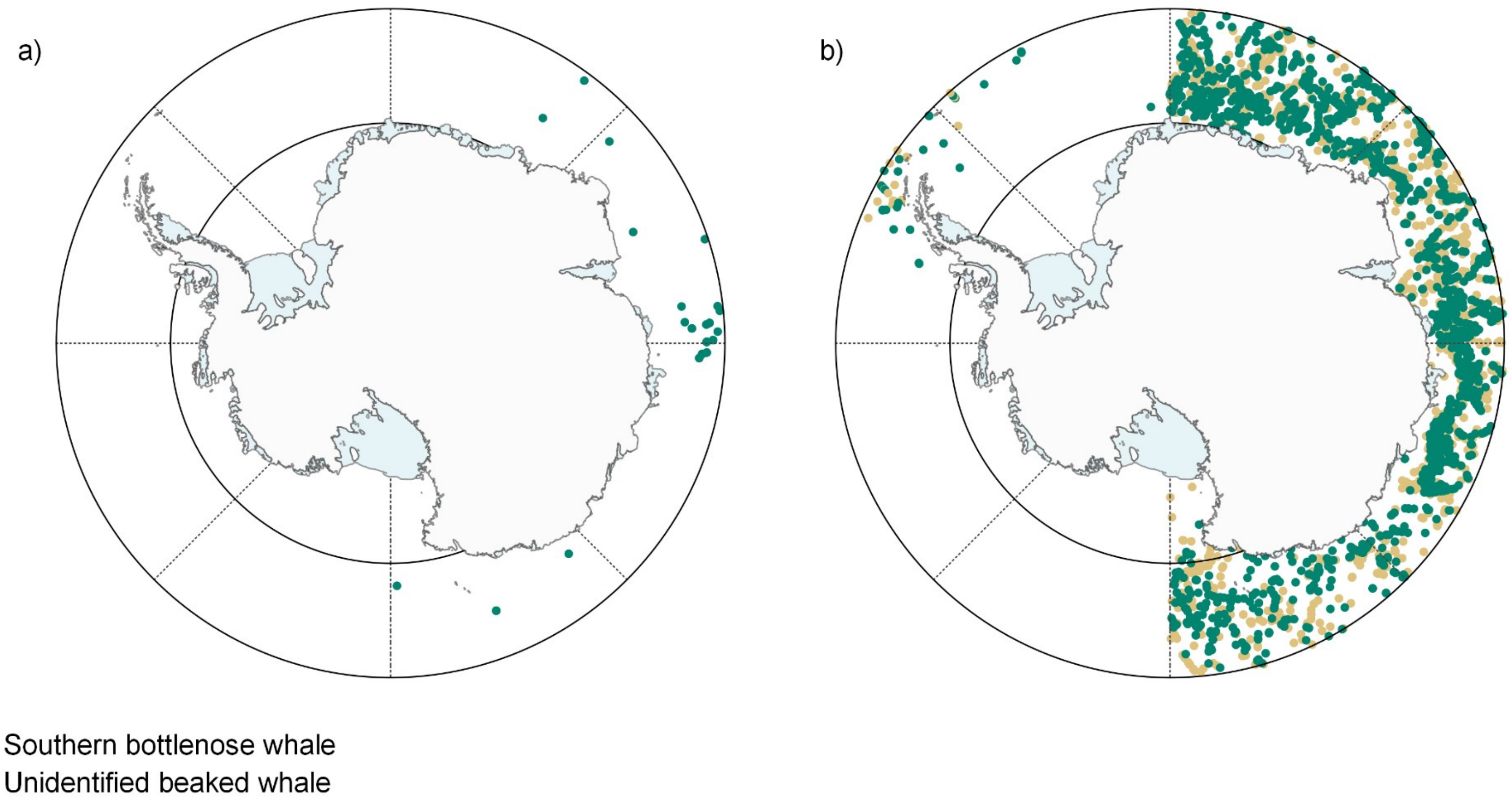
Beaked whales

All Antarctic beaked whale species are classified as 'Least Concern' on the IUCN Red List since sightings are not rare in parts of their ranges (Baird et al., 2020; Brownell, 2020; Lowry & Brownell, 2020; Pitman & Brownell, 2020; Pitman & Taylor, 2020). These species have a circumpolar distribution in the Southern Hemisphere, occurring between the ACC and the ice edge, often along the continental slope (Laws, 1977; Kasamatsu & Joyce, 1995; Scheidat et al., 2007; Santora & Brown, 2010). However, little species-specific data exist to describe spatio-temporal trends. Southern bottlenose whales and Arnoux's beaked whales are distributed in deep, pelagic water as far south as the ice edge (Erbe et al., 2019; Brownell, 2020; Lowry & Brownell, 2020), although Arnoux's beaked whales have also been recorded in deep coastal waters and canyons near the Antarctic Peninsula (Friedlaender et al., 2010) and in ice-covered waters (Scheidat et al., 2011). Southern bottlenose whale sightings increase with depth, and have been associated with close proximity to the APF (Bassoi et al., 2020), as well as both oceanic waters and shelf-slopes near the South Shetland Islands, indicating potential for population-specific habitat preferences (Santora & Brown, 2010). Gray's beaked whale, strap-toothed whale, and Cuvier's beaked whale sightings are generally located farther north, away from the ice edge (Erbe et al., 2019; Baird et al., 2020; Pitman & Brownell, 2020; Pitman & Taylor, 2020). Limited sightings and strandings data suggest that shifts in space-use within the Southern Ocean and/or to higher latitudes are possible, but any migration patterns remain unknown due to the paucity of data for most species (van Waerebeek et al., 2010). There are no regions in the study area where sightings of any beaked whale species are common.

Beaked whales are difficult to detect at sea given their inconspicuous surface behaviour, rare occurrence (for some species), prolonged dive times, short surface intervals, and sensitivity to noise (Kasamatsu et al., 2000; Branch & Butterworth, 2001; Santora & Brown, 2010). As a result, there is a clear lack of species-specific data, and abundance estimates for beaked whale species in the study region remain unknown. Surveys conducted in the late 1990s resulted in a corrected abundance estimate for all beaked whales of about 599,300 individuals between the APF and as far south as the Ross Sea (Kasamatsu & Joyce, 1995). The majority of beaked whale sightings in the Antarctic have been confirmed as southern bottlenose whales and are estimated to account for up to 97% of records (Branch & Butterworth, 2001).

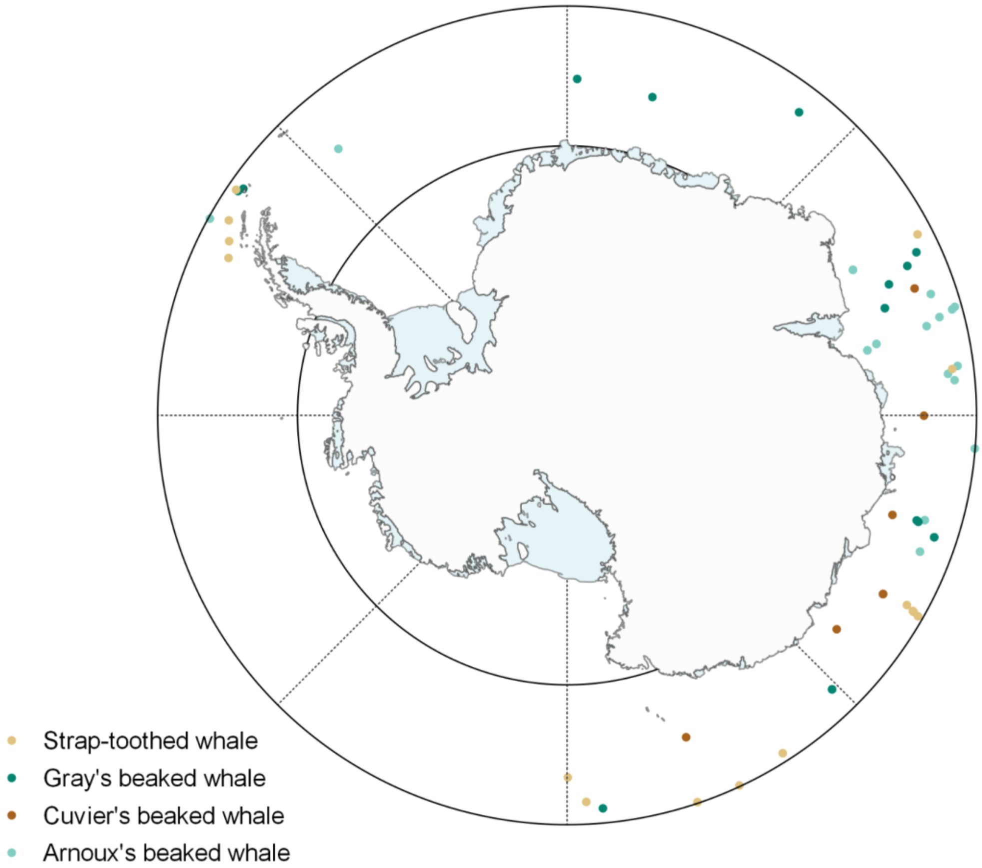
It is clear that large gaps remain in understanding population dynamics and trends in space-use, both globally and in the Southern Ocean. Continued research and more sightings are needed to estimate species-specific abundance south of 60°S, and to assess how anthropogenic threats (e.g. noise pollution) will impact Antarctic beaked whale species.

Figure B. 19: Distribution of southern bottlenose whales (*Hyperoodon planifrons*) south of 60°S and unidentified beaked whales from a) catch data and b) available sighting data. Solid lines demarcate 60 and 70°S and dashed lines represent longitude in 45° increments.



Source: Author's own.

Figure B. 20: Distribution of other beaked whale species (*Mesoplodon layardii*, *Ziphius cavirostris*, *Mesoplodon grayi*, *Berardius arnuxii*) south of 60°S from available sighting data. Solid lines demarcate 60 and 70°S and dashed lines represent longitude in 45° increments.



Source: Author’s own.

Long-finned pilot whale

Presently, all long-finned pilot whales in the Antarctic region are assumed to be part of the southern long-finned pilot whale subspecies (*Globicephala melas edwardii*) (Davies, 1960), and their presence in the Antarctic is thought to be scarce (Hanson & Erickson, 1985). The IUCN Red List designates this species as ‘Least Concern’ (Minton et al., 2018), but the actual abundance of long-finned pilot whales in the Antarctic is unclear. The abundance of this population south of the APF is considered to be 200,000 individuals, though this includes 50-60°S between 60°W-160°E longitudes (Kasamatsu & Joyce, 1995).

Occurrence of this species is highest in the northernmost regions of the Antarctic (Kasamatsu & Joyce, 1995; van Waerebeek et al., 2010). Most animals likely remain north of the APF, but in the summer season they may be found as far south as the Bellingshausen Sea (van Franeker, 2002). Southern Ocean Cetacean Ecosystem Program (SOCEP) survey data revealed concentrations between 90°E–110°E and 130°E–150°E off the continental shelf and at the base of the steep shelf-slope (van Waerebeek et al., 2010). In the South Pacific sector south of 60°S, encounter rates peaked between 170-160°W, with a smaller peak between 110-120°W. The highest encounter rates in the entire region for this species were observed in the second half of January

(Kasamatsu & Joyce, 1995). Sightings are rare south of 60°S. More data are needed to determine what proportion of the southern subspecies are found in these waters.

Figure B. 21: Distribution of long-finned pilot whales (*Globicephala melas*) south of 60°S from available sighting data. Solid lines demarcate 60 and 70°S and dashed lines represent longitude in 45° increments.

Source: Author's own.

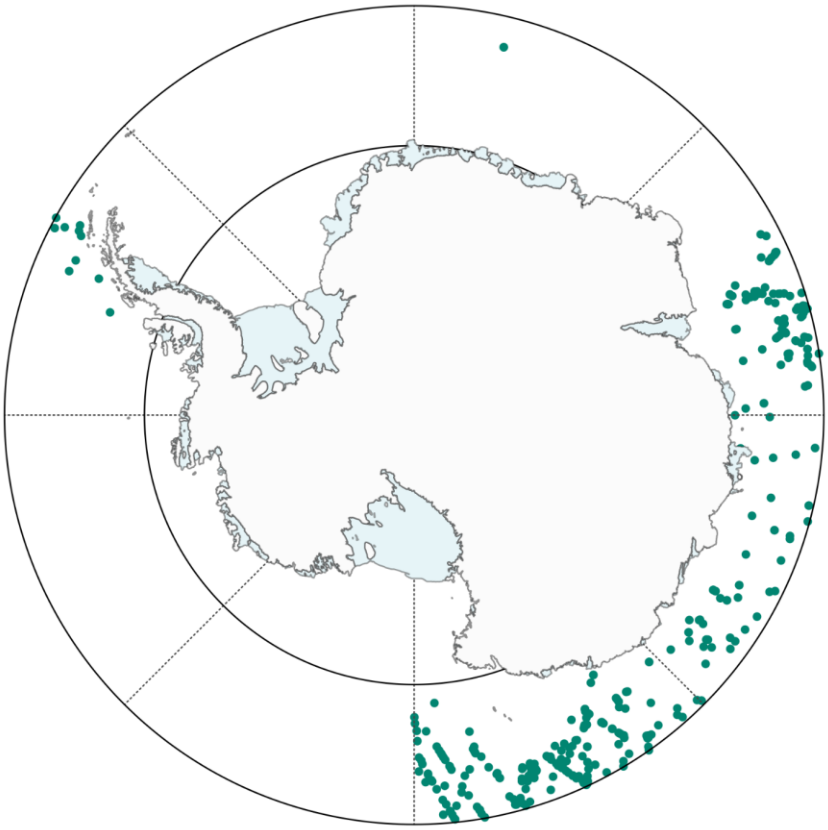
Hourglass dolphin

Hourglass dolphin abundance in Antarctic waters has been estimated at 144,300, but this number includes sightings north of 60°S between 60°W and 160°E (Kasamatsu & Joyce, 1995). Though the IUCN Red List indicates the status of this species is 'Least Concern' (Braulik, 2018), this may not be representative of the population south of 60°S. This species is most frequently seen in northern Antarctic waters (Kasamatsu & Joyce, 1995), and most individuals likely do not go as far south as the APF during the majority of the year (van Franeker, 2002). They have been observed as far south as the Bellingshausen Sea during summer months, with an estimated abundance of 10,000 individuals south of 60°S (van Franeker, 2002). Presence in this region increases in February and March, coinciding with rises in sea surface temperature (Kasamatsu & Joyce, 1995).

Hourglass dolphins have a circumpolar distribution in open water near the ACC, over the shelf-slope, and near sea ice (Thiele et al., 2000; Ropert-Coudert et al., 2014). Longitudinal gaps in their distribution occur between 80-150°W and 0-40°W. They can be found the farthest south between 150°E and 150°W, and are more frequent in southern waters (as far as 67°S) of the South Pacific sector than the South Atlantic (Kasamatsu & Joyce, 1995). IWC SOC (IWC's

Southern Ocean Collaboration Working Group Program) surveys have recorded hourglass dolphin sightings south of 66°S off the WAP (van Waerebeek et al., 2010). They concentrate in areas associated with frontal zones and eddies (Thiele et al., 2000), as well as warmer sea surface temperatures and close proximity to the APF (Bassoi et al. 2020). SOCEP surveys found concentrations of this species near the continental shelf and shelf-slope (van Waerebeek et al., 2010). In East Antarctica, hourglass dolphins have been found between 63-64.3°S and in close proximity to the southern boundary of the ACC (Thiele et al., 2000). Off the northern WAP, hourglass dolphin sightings in southern Drake Passage to the north of the South Shetland Islands increased with proximity to the southern ACC boundary (Santora, 2012). This species has been found north of Elephant Island in the South Shetland Islands (Santora, 2012) and in offshore, deep water beyond the shelf-break (Thiele et al., 2000; Santora, 2012).

Figure B. 22: Distribution of hourglass dolphins (*Lagenorhynchus cruciger*) south of 60°S from available sighting data. Solid lines demarcate 60 and 70°S and dashed lines represent longitude in 45° increments.



Source: Author's own.

Killer whale

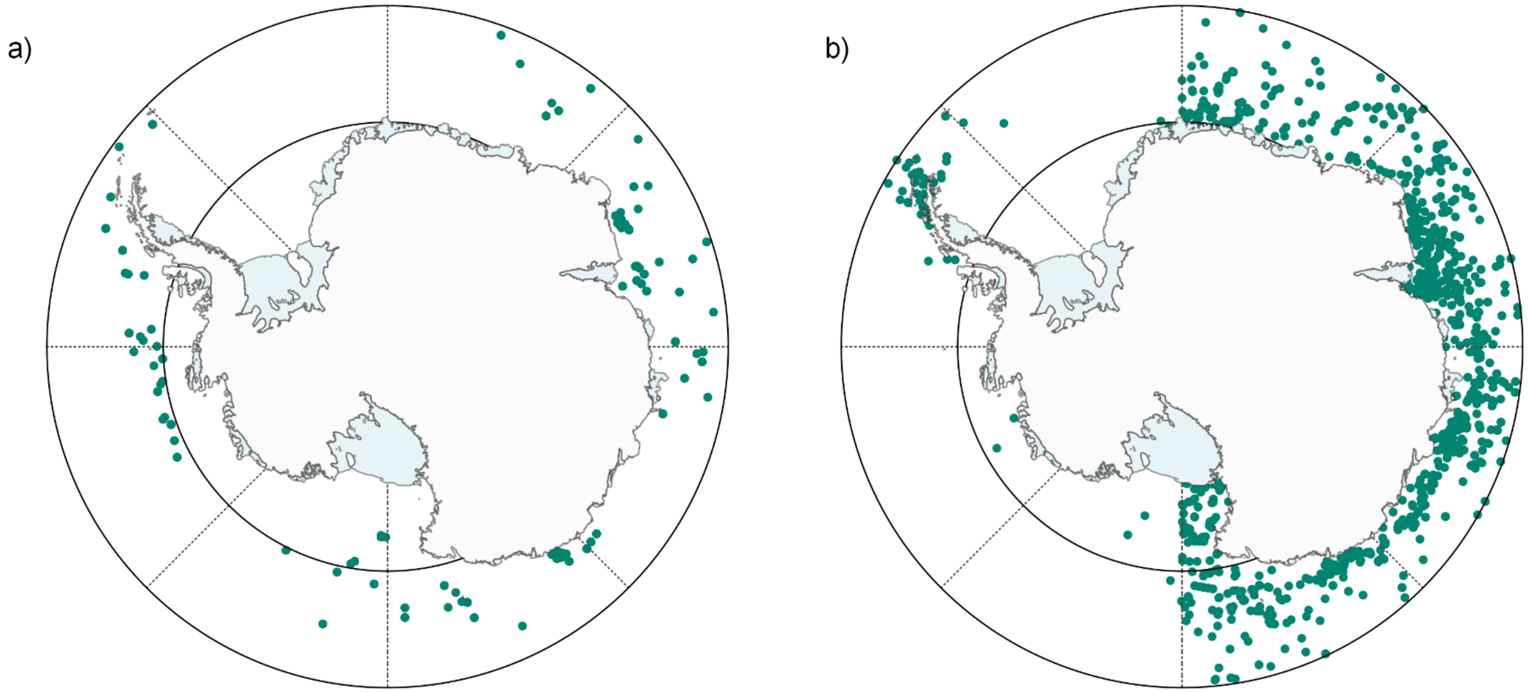
Globally, killer whales are classified as 'Data Deficient' on the IUCN Red List (Reeves et al., 2017), and there is a clear lack of data related to abundance and movements of Antarctic ecotypes. At least four morphologically and culturally unique killer whale types occur throughout the Antarctic (de Bruyn et al., 2013; Erbe et al., 2019), and are referred to as either morphotypes or ecotypes in the literature. Although there is still some debate on the classification of this species or species-complex, for the purpose of this review Antarctic killer whales will be referred to as distinct ecotypes (Type A, Type B (big), Type B (small), Type C, and Type D), where possible. Type D killer whales are distributed in subantarctic and temperate waters north of 60°S (de Bruyn et al., 2013); the remainder of this section will focus on the other ecotypes.

Large-scale, comprehensive surveys of odontocete abundance in the Antarctic were conducted from the late 1970s-1980s, and resulted in a corrected abundance estimate of 80,400 killer whales south of the APF (Kasamatsu & Joyce, 1995). Building on these data, three circumpolar surveys conducted on IWC/IDCR and SOWER cruises (1978/79-1983/84, 1985/86-1990/91, 1991/92-1997/98) were used to generate the following killer whale abundance estimates: 91,310 individuals, 27,168 individuals, and 24,790 individuals, respectively (Branch & Butterworth, 2001). While these are the best available estimates for total killer whale abundance in the Antarctic, there are caveats related to study design (e.g., the first circumpolar survey followed the ice edge, resulting in a positively biased estimate (Branch & Butterworth, 2001; Leaper et al., 2008)). The data are also more than 30 years old, so more research is needed to estimate current abundance and look at inter- and intra-annual trends.

Antarctic killer whales have a circumpolar distribution, ranging in all habitats including open ocean, shelf waters, along the coastline, and within pack-ice (Pitman & Ensor, 2003; van Waerebeek et al., 2010; Ropert-Coudert et al., 2014; Erbe et al., 2019). Previous research showed that encounter rate increased south of 62°S, peaking at 66°S in association with the general location of the ice edge (Kasamatsu & Joyce, 1995; Kasamatsu et al., 2000). Limited tracking data south of 60°S of Type A, Type B, and Type C killer whales have revealed differences in space-use, although the sample sizes make it difficult to infer trends for the ecotypes as a whole (Andrews et al., 2008; Durban & Pitman, 2012; Fearnbach et al., 2019; Lauriano et al., 2020). Differences in space-use suggest that any fine-scale movements throughout the Antarctic, or larger movements into higher latitudes, are likely driven by prey preferences and availability. Type A killer whales hunt cetaceans and seals and are distributed in pelagic waters around the Antarctic continent throughout the summer (van Waerebeek et al., 2010; de Bruyn et al., 2013). Type B (big) killer whales hunt pinnipeds in pack ice in summer, while Type B (small) killer whales feed on penguins throughout pack ice, mostly near the Antarctic Peninsula (Pitman & Ensor, 2003; de Bruyn et al., 2013). Type C killer whales have a diet consisting of fish and are distributed throughout the pack ice in summer (van Waerebeek et al., 2010; de Bruyn et al., 2013), and may be associated with both shelf and slope in the Ross Sea (Ballard et al., 2012). Winter distributions are unknown, except for Type B (small) which move to subtropical waters (Durban & Pitman, 2012; de Bruyn et al., 2013). Winter visual and acoustic surveys have recorded Type C killer whales in polynyas and along the fast-ice edge (Gill & Thiele, 1997; Van Dam & Kooyman, 2004), indicating that at least some individuals may be resident year-round.

These ecotypes occupy unique roles in their ecosystems given their distinct diet, movement patterns, and behaviour. Knowledge of abundance of Type A, Type B (big and small), and Type C killer whales is critical in order to assess their vulnerability to changing environments and anthropogenic impacts. Research conducted in Wilkes Land, East Antarctica estimated a winter abundance of about 40 Type A killer whales in the sea ice, associated with polynyas and the fast-ice edge (Gill and Thiele, 1997). A long-term mark-recapture study of Type A killer whales off the WAP estimated a summer abundance of about 91 individuals in 2009/10 that increased to 149 individuals in 2016/17, potentially in response to a decrease in sea ice or an increase in prey abundance (Fearnbach et al., 2019). A similar study conducted over 7 summers in McMurdo Sound identified two groups of Type C killer whales: ‘regulars’ which displayed high site-fidelity (comprised of about 73 individuals), and ‘irregulars’ (comprised of about 397 individuals) (Pitman et al., 2018). More data are required to look at spatio-temporal trends in Type C killer whale abundance in McMurdo Sound, and throughout the Ross Sea, especially given different patterns in space-use within the ecotype (Pitman et al., 2018). To the best of our knowledge, and based on the literature available for this review, there are no abundance estimates for Type B killer whales, and there is a paucity of data for all Antarctic ecotypes throughout their ranges.

Figure B. 23: **Distribution of killer whales (*Orcinus orca*) south of 60°S from a) catch data and b) available sighting data. Solid lines demarcate 60 and 70°S and dashed lines represent longitude in 45° increments.**



Source: Author’s own.

Spectacled porpoise

The spectacled porpoise is understudied, and although the IUCN classification is ‘Least Concern’, they are rarely seen in Antarctic waters and have no current abundance estimates (Dellabianca et al., 2018; Erbe et al., 2019). The available literature indicates that spectacled porpoise has a circumpolar distribution (Baker, 1977; Goodall & Schiavini, 1995; Sekiguchi et al., 2006); however, most reported strandings and sightings lie north of 60°S (van Waerebeek et al., 2010). There are no confirmed temporal patterns in space-use (van Waerebeek et al., 2010).

Figure B. 24: Distribution of spectacled porpoise (*Phocoena dioptrica*) south of 60°S from available sighting data. Solid lines demarcate 60 and 70°S and dashed lines represent longitude in 45° increments.

Source: Author’s own.

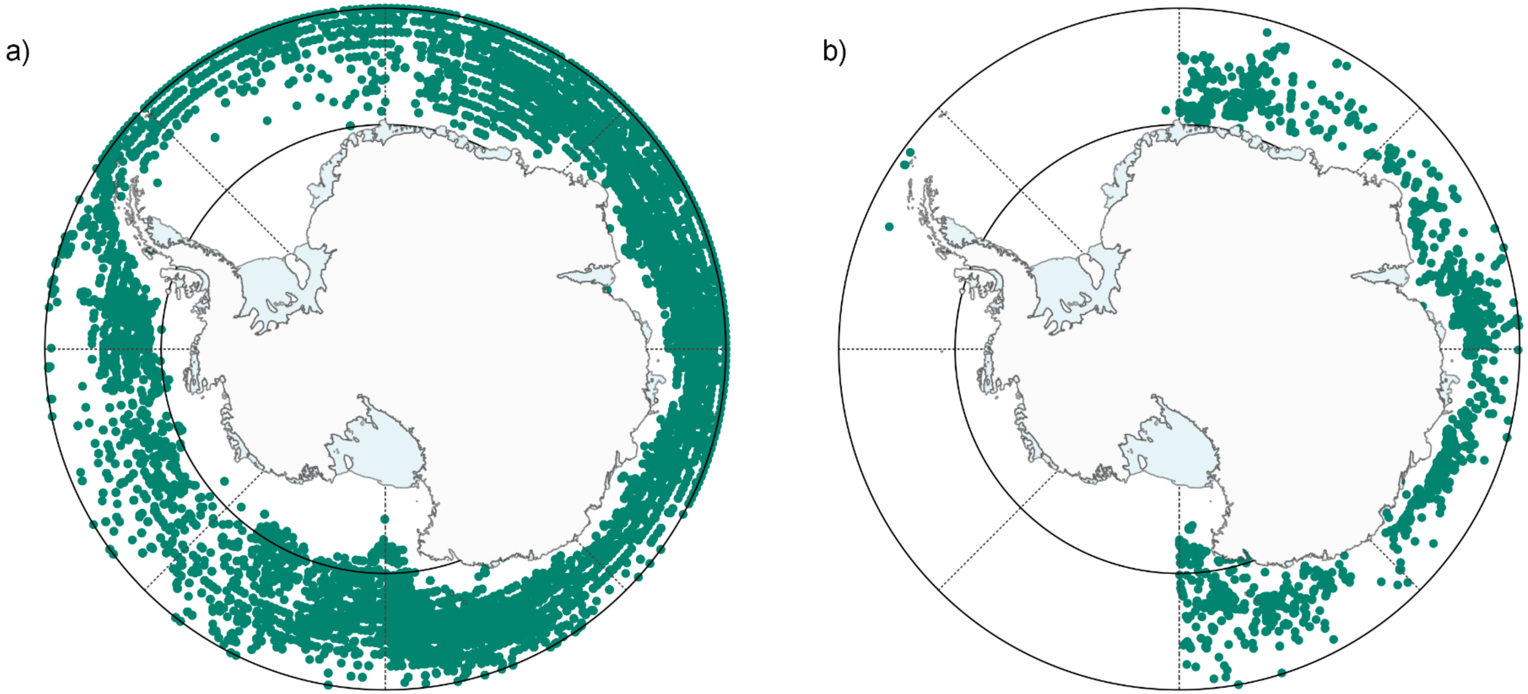
Sperm whale

Sperm whales are listed as ‘Vulnerable’ with an estimated global abundance of 360,000 individuals (Ropert-Coudert et al., 2014; Lowther, 2018; Taylor et al., 2019). Approximately 10,000 to 12,000 individuals are estimated to occur south of 60°S, reduced to 1,000 individuals in the summer population (van Franeker, 2002; Ropert-Coudert et al., 2014). The highest population estimate south of the APF to date was 599,300 individuals based on line transect surveys (Kasamatsu & Joyce, 1995). Three IWC/SOWER surveys between 1978 and 1979 estimated circumpolar abundance at 5,400 individuals, 10,000 individuals, and 8,300 individuals, respectively (Branch & Butterworth, 2001). These numbers, however, are likely underestimated because they assumed 100% detection, which is unlikely for the species given long dive times (Branch & Butterworth, 2001).

Sperm whale distribution south of 60°S is latitudinally segregated by size and sex. Females are rarely found south of 40°S while male school sizes decrease further south (Branch & Butterworth, 2001). It is thought that sperm whales migrate to lower latitudes in winter months and their numbers increase in Antarctic waters throughout the summer, peaking in early January (van Waerebeek et al., 2010). Acoustic monitoring off East Antarctica showed more detections of sperm whales during summer than in the spring or fall (Miller & Miller, 2018). Sperm whales were statistically less likely to be present with increasing ice cover and no sperm whales were detected during ice-heavy winter months (Miller & Miller, 2018). Although understanding temporal migration patterns requires further research (Meister, 2017), it is likely that males head back to warmer waters in winter to mate (Ropert-Coudert et al., 2014). Historical distribution data of mature males show they can be found as far south as 74°S in the Ross Sea and are regularly south of 66°S (Ropert-Coudert et al., 2014). Surveys off East Antarctica recorded sperm whales in close proximity to the Antarctic Divergence and southern boundary of the ACC (Thiele et al., 2000). Sightings have also been recorded between King Edward VII Peninsula, Marie Byrd Land on the Ross Sea and Marguerite Bay, off the WAP (Ainley et al., 2007). Sperm whales preferentially distribute in waters further south than 60°S, with the southernmost sighting in the Ross Sea at 74°S (Kasamatsu & Joyce, 1995).

Sperm whales have been observed farther away from the ice edge (Kasamatsu and Joyce, 1995; Erbe et al., 2019), and tend to be distributed in deep water (Kasamatsu et al., 2000). Interestingly, they were not found over the continental shelf or shelf break, but were concentrated in waters over the shelf-slope and plane (Kasamatsu et al., 2000). An explanation for this pattern is that sperm whale distribution is prey-dependent, reflecting availability of deep sea squids (Kasamatsu et al., 2000). Changes in the distribution and seasonal presence of sperm whales relate to conditions optimal for squid schooling (van Waerebeek et al., 2010), and have been associated with frontal zones, eddies, and the southern perimeter of a warm water intrusion known as Modified Circumpolar Deep Water (MCDW) (Thiele et al., 2000). The warm water intrusion and bathymetry could support preferential environmental conditions for squid, and therefore drive the distribution of sperm whales (Thiele et al., 2000). Despite being one of the better studied cetaceans in Antarctica, there are still knowledge gaps in the current understanding of abundance, distribution, and inter- and intra-annual trends (Kasamatsu and Joyce, 1995; Whitehead, 2002).

Figure B. 25: **Distribution of sperm whales (*Physeter macrocephalus*) south of 60°S from a) catch data and b) available sighting data. Solid lines demarcate 60 and 70°S and dashed lines represent longitude in 45° increments.**



Source: Author's own.

B.4 Discussion

The Southern Ocean is a critically important area for both seasonal migrators and endemic marine mammal species. Contemporary data on the abundance and distribution of many Antarctic species are limited despite requiring this information for management and conservation efforts (Erbe et al., 2019). As anthropogenic activity in the Antarctic increases and people become more aware of this issue, a study compiling information on spatio-temporal distribution and abundance of Antarctic marine mammals is urgently needed to accurately define noise thresholds and metrics for mitigation strategies (Erbe et al., 2019).

This review allowed us to summarize spatio-temporal distribution and abundance of Antarctic marine mammals south of 60°S and assess patterns across the available literature. Our bibliometric analysis showed that the majority of the reviewed literature were concentrated around a select few species (e.g., minke whales, humpback whales, crabeater seals) with some species mentioned in 10 or fewer of the publications (e.g., Arnoux's beaked whale, Gray's beaked whale, Cuvier's beaked whale, strap-toothed whale, spectacled porpoise, long-finned pilot whale, southern right whale) (Figure B. 2). The available literature was primarily based on visual surveys, although acoustic monitoring, telemetry, and DNA analyses are also useful for understanding population estimates and space-use. Most research occurred in the late 20th and early 21st centuries (between 1990-2020), and in recent years focused on minke whales, humpback whales, killer whales, and Antarctic fur seals (Figure B. 3, Figure B. 4 and Figure B. 5). Overall, publications on mysticetes were greatest, followed by pinnipeds, and odontocetes.

A systematic review of these papers identified data gaps as a result of outdated estimates or data deficiencies (Table B. 5). Studies of spatio-temporal abundance and population trends for most species throughout the region are limited by the remoteness of their preferred habitat, cryptic nature of some species, and the logistics and resources required to conduct population-level studies in the Antarctic. Perhaps the most available information on marine mammal abundance in the Antarctic is related to the largest whale species, which were heavily exploited by whaling, although data are still lacking for species such as the sei whale. The paucity of data on hourglass dolphin, long-finned pilot whales, southern right whales, and spectacled porpoise could just be because 60°S represents the southernmost portion of their range. However, comparatively few studies are available on the ecology of these species (Figure B. 1 and Figure B. 2). Ross seal sightings are rare (Siniff, 1991; van Franeker, 2002), further complicated by their preference for dense pack ice (Bengtson et al., 2011). Studies using helicopters, drones, and satellite imagery will help contribute to the limited available knowledge of Ross seal abundance, as well as for other species associated with dense sea ice habitat. While southern bottlenose whales are the most sighted beaked whale species in the Antarctic (Branch & Butterworth, 2001), there is no region where sightings are considered common. The majority of data and literature available for this review did not distinguish among beaked whale species, hindering a full assessment.

Survey effort is not homogenous temporally (i.e., over the last few decades as some whale populations recover from whaling, or seasonally) or spatially throughout the study area. All line-transect survey effort and sightings data we could access came from summer months (Figure B. 6). Surveys in spring, fall, and winter are needed. In addition, generating an accurate picture of circumpolar abundance and distribution would also benefit from dedicated research focused in less-frequented parts of the Antarctic, including the regions around the Bellingshausen, Amundsen, and Ross Seas (IWC management areas I, VI, and V). The eastern Ross Sea is densely covered in multi-year pack ice, even during summer, so this region is particularly difficult to access and study (Ackley et al., 2003). It is important to note that estimates of abundance are influenced by the behaviour and detectability of the study species, as well as the survey methodology. Comprehensive, circumpolar abundance estimates were not available for most species, and many of the reported regional abundances are likely underestimates (e.g., as a result of low detection rates). Patterns of distribution and/or migration are further complicated by variation in space-use within species and ecotypes, as has been found for leopard seals, Weddell seals, blue whales, fin whales, humpback whales, and killer whales.

The information we have compiled here covers a breadth of information on historical and current information for understanding patterns in marine mammal distribution and abundance. Such information is necessary to assess population changes over time and space, and is of particular importance in a part of the world currently experiencing the dynamic, additive effects of both environmental and anthropogenic change (Hoegh-Guldberg & Bruno, 2010).

B.4.1 Caveats and limitations

Although our intent was to review spatial and temporal patterns in marine mammal distribution in the Antarctic, it emerged that all effort-corrected sightings data that we could access came from systematic line-transect surveys conducted in summer months. As a result, we present only spatial patterns in search effort and animal distribution. Patterns of seasonality were described in this review whenever possible and were usually a result of satellite tracking data rather than survey data. The paucity of surveys conducted outside of summer months limits the potential to fully assess circumpolar effort south of 60°S. Information on seasonality is included in the text to support our understanding of spatio-temporal variability in abundance and distribution of these species.

As many as 70 research stations, representing 29 countries, may be active in the Antarctic[16]. By restricting our literature review to primary (peer-reviewed) papers published in English, and data shared to open access databases such as OBIS-SEAMAP and PANGAEA, we are aware that we may be missing studies that result in grey literature publications in languages other than English. We mitigated this risk by consulting reports to international organizations and bodies (CCAMLR, IWC, IUCN) with international representation. We welcome the opportunity to add data that our review missed.

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[16] https://oceanwide-expeditions.com/blog/a-look-into-the-international-research-stations-of-antarctica

B.5 Appendix to Annex 2

B.5.1 Data table

Table B. 6: Data sources captured during the literature search phase of Antarctic marine mammal distribution and abundance.

Source	Year	Method	Species Group	Citation
ANT23-8c	2006-2007	aerial line-transect	cetaceans	Scheidat & Herr (2018)
ANT25-2	2008-2009	aerial line-transect	cetaceans	Scheidat et al. (2018)
ANT27-2	2010-2011	aerial line-transect	cetaceans	Herr et al. (2018a)
ANT28-2	2011-2012	aerial line-transect	cetaceans	Herr et al. (2018b)
ANT29-3	2012-2013	aerial line-transect	cetaceans	Herr & Siebert (2018)
IWC-SOWER	1978-2010	vessel line-transect	cetaceans	IWC
Rob Williams	2000-2002	vessel line-transect	cetaceans	Williams et al. (2006)
SCAR	2007-2014	CTD-SRDL tag	pinnipeds	Atlas of Living Australia (2019)
SCAR	2006-2011	biopsy samples	cetaceans	Schmitt et al. (2018)
SCAR	1995-2004	at-sea sightings (including incidental)	cetaceans	Raymond & Kool (2020a)
SCAR	2006	at-sea sightings	cetaceans	Australian Antarctic Data Centre (2006)
SCAR	2015	biopsy samples	cetaceans	Double & Connell (2018)
Tracey Rogers	1999-2000	acoustic	pinnipeds	Rogers et al. (2013); Shabangu & Rogers, (2021)
Weddell Seal Sightings, Vestfold Hills, Antarctica	1973-2006	ground-based sightings	pinnipeds	Australian Antarctic Data Centre (2020)
APIS	1984-2000	vessel and aerial sightings	pinnipeds	Raymond & Kool (2020b)

Source	Year	Method	Species Group	Citation
Leopard and Weddell seal program 1999/2002	1999-2002	ground-based, vessel, and aerial sightings	pinnipeds	Rogers & Hogg (2018)
NIWA	2006	at-sea sightings	cetaceans & pinnipeds	NIWA (2015)
ANT-XXII_3	2005	vessel	cetaceans	Burkhardt (2009a)
ANT-XXIII_2	2005	vessel	cetaceans	Burkhardt (2009b)
ANT-XXIII_3	2006	vessel	cetaceans	Burkhardt (2009c)
ANT-XXIII_4	2006	vessel	cetaceans	Burkhardt (2009d)
ANT-XXIII_6	2006	vessel	cetaceans	Burkhardt (2009e)
ANT-XXIII_7	2006	vessel	cetaceans	Burkhardt (2009f)
ANT-XXIII_8	2006-2007	vessel	cetaceans	Burkhardt (2009g)
ANT-XXIII_9	2007	vessel	cetaceans	Burkhardt (2009h)
ANT-XXIV_2	2007-2008	vessel	cetaceans	Burkhardt (2009i)
ANT-XXIV_3	2008	vessel	cetaceans	Burkhardt (2009j)
ANT-XXV_2	2008-2009	vessel	cetaceans	Burkhardt (2009k)
ANT-XXV_3	2009	vessel	cetaceans	Burkhardt (2009l)
OBIS 103150014	1977-2006	vessel	cetaceans & pinnipeds	Raymond & Watts (2020)
OBIS 103151600	2006-2007	various	cetaceans & pinnipeds	Danis (2020)
OBIS 103152294	1999	Argos tracking	pinnipeds	Pea, (2020)
OBIS 103150599	1929-1931	vessel	cetaceans	Watts (2020b)
OBIS 103152542	2018-2019[17]	vessel	cetaceans & pinnipeds	Bowden & Constantine (2020)
OBIS 103152579	2011	vessel	cetaceans	Vishnyakova (2016)
OBIS 103150150	1995-2004	vessel	cetaceans	Gorton & Thiele (2020)
OBIS 64	1974-2002	vessel	cetaceans & porpoises	Maughan & Arnold (2010)
OBIS 103152363	1910-1913	vessel	cetaceans	Southwestern Pacific OBIS (2014a)

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[17] 2019 Antarctic voyage TAN/NIWA data from Dr. Rochelle Constantine and the Marine Mammal Ecology Group

Source	Year	Method	Species Group	Citation
OBIS 103152399	1922-1952	various	cetaceans	Southwestern Pacific OBIS (2014b)
OBIS 103150607	1991-1997	various	cetaceans	Watts (2009)
OBIS 103152377	1939-1941	various	pinnipeds	SWPRON (2019)
OBIS 70	1995-1997	tracking	pinnipeds	Macleod (2012)
OBIS 103152433	2017	various	cetaceans	Pirotta (2020)
MEOP-CTD	2004-2017	CTD-SRDL tag	pinnipeds	Bornemann et al. (2015); de Bruyn et al. (2015); Treasure et al. (2017)
CCAMLR-SOWER-2000	2000	vessel	cetaceans	Made available via Natalie Kelly, AAD
SOCEP	1995-2004	vessel	cetaceans	Made available via Natalie Kelly, AAD
Retrospective Analysis of Antarctic Tracking Data from the Scientific Committee on Antarctic Research	1999-2021	tracking	pinnipeds & cetaceans	Ropert-Coudert et al. (2020)
SCALE (MV SA Agulhas II, 2019), PS111 (RV *Polarstern*, 2018), and S55 (MV SA Agulhas II, 2016)	2016; 2018-2019	Argos tracking	pinnipeds	Wege et al. (2021)
IWC individual catch database	1928-2019	whale catches	cetaceans	Allison (2020)

B.5.2 List of data sources in Annex 2

Allison, C. (2020) IWC individual catch database Version 7.1; Date: 23 December 2020

Atlas of Living Australia (2019). IMOS - AATAMS Facility Satellite Relay Tagging Program - Delayed mode data. Occurrence dataset https://doi.org/10.15468/qhco7i. Data downloaded on 2021-01-08

Australian Antarctic Data Centre (2006). Cetacean Sightings Survey and Southern Ocean Cetacean Program - BROKE-West. Occurrence Dataset https://doi.org/10.15468/7pkncj.Data downloaded on 2021-01-08

Australian Antarctic Data Centre (2020). Weddell Seal Sightings, Vestfold Hills, Antarctica. Occurrence dataset https://doi.org/10.15468/pljlvy

Bornemann, H., Bester, M. N., de Bruyn, P. J. N., Márquez, M. E. I., McIntyre, T., Plötz, J., Schröder, M., and Tosh, C. A., (2015): Ocean temperature and salinity measured by CTD SRDLs deployed on southern elephant seals from King George Island with links to datasets. PANGAEA, https://doi.org/10.1594/PANGAEA.150009

Bowden, D., Constantine, R., (2020): Marine mammal observations from the TAN1802 voyage to the Ross Sea, Antarctica. v1.0. The National Institute of Water and Atmospheric Research (NIWA). Dataset/Occurrence. https://nzobisipt.niwa.co.nz/resource?r=tan1802marinemammalsightings&v=1.0

Burkhardt, E. (2009a): Whale sightings during POLARSTERN cruise ANT-XXII/3. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, PANGAEA, https://doi.org/10.1594/PANGAEA.729027

Burkhardt, E. (2009b): Whale sightings during POLARSTERN cruise ANT-XXIII/2. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, PANGAEA, https://doi.org/10.1594/PANGAEA.729030

Burkhardt, E. (2009c): Whale sightings during POLARSTERN cruise ANT-XXIII/3. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, PANGAEA, https://doi.org/10.1594/PANGAEA.729031

Burkhardt, E. (2009d): Whale sightings during POLARSTERN cruise ANT-XXIII/4. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, PANGAEA, https://doi.org/10.1594/PANGAEA.729032

Burkhardt, E. (2009e): Whale sightings during POLARSTERN cruise ANT-XXIII/6. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, PANGAEA, https://doi.org/10.1594/PANGAEA.729034

Burkhardt, E. (2009f): Whale sightings during POLARSTERN cruise ANT-XXIII/7. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, PANGAEA, https://doi.org/10.1594/PANGAEA.729035

Burkhardt, E. (2009g): Whale sightings during POLARSTERN cruise ANT-XXIII/8. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, PANGAEA, https://doi.org/10.1594/PANGAEA.729036

Burkhardt, E. (2009h): Whale sightings during POLARSTERN cruise ANT-XXIII/9. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, PANGAEA, https://doi.org/10.1594/PANGAEA.729037

Burkhardt, E. (2009i): Whale sightings during POLARSTERN cruise ANT-XXIV/2. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, PANGAEA, https://doi.org/10.1594/PANGAEA.729040

Burkhardt, E. (2009j): Whale sightings during POLARSTERN cruise ANT-XXIV/3. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, PANGAEA, https://doi.org/10.1594/PANGAEA.729041

Burkhardt, E. (2009k): Whale sightings during POLARSTERN cruise ANT-XXV/2. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, PANGAEA, https://doi.org/10.1594/PANGAEA.728270

Burkhardt, E. (2009l): Whale sightings during POLARSTERN cruise ANT-XXV/3 (LOHAFEX). Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, PANGAEA, https://doi.org/10.1594/PANGAEA.729044

Danis, B., (2020). ANTXXIII-8 Birds and Mammals. Data downloaded from OBIS-SEAMAP (http://seamap.env.duke.edu/dataset/103151600) on 2021-02-09 and originated from OBIS (https://obis.org/dataset/d815b624-43e6-4e3e-9136-094353e776f8)

Double, M., and Connell, D. (2018). Sample summary and analysis of biopsy samples collected during the New Zealand Australian Antarctic Ecosystems Voyage 2015. Australian Antarctic Data Centre. Occurrence dataset https://doi.org/10.15468/pmjowl. Data downloaded on 2021-01-08

de Bruyn, P. J. N., Bester, M. N., Bornemann, H., McIntyre, T., Plötz, J., and Tosh, C. A., (2015): Ocean temperature and salinity measured by CTD SRDLs deployed on southern elephant seals from Marion Island with links to datasets. PANGAEA, https://doi.org/10.1594/PANGAEA.150008

Gorton, R., and Thiele., D., (2020). Cetacean Sightings Survey and Southern Ocean cetacean program. Data downloaded from OBIS-SEAMAP (http://seamap.env.duke.edu/dataset/103150150) on yyyy-mm-dd and originated from OBIS (https://obis.org/dataset/2ab04179-c3e5-4754-9df5-65d3b3e0dbcd)

Herr, H., Lehnert, L. S., and Siebert, U. (2018a): Aerial cetacean survey Southern Ocean 2010/2011. PANGAEA, https://doi.org/10.1594/PANGAEA.894934

Herr, H., Lehnert, L. S., and Siebert, U. (2018b): Aerial cetacean survey Southern Ocean 2011/2012. PANGAEA, https://doi.org/10.1594/PANGAEA.894924

Herr, H., and Siebert, U. (2018): Aerial cetacean survey Southern Ocean 2012/2013. PANGAEA, https://doi.org/10.1594/PANGAEA.894914

Macleod, K., (2012). SMRU Elephant Seal Pup Tracking 1995-1996. Data downloaded from OBIS-SEAMAP (http://seamap.env.duke.edu/dataset/70) on 2021-02-10.

Maughan, B., and Arnold, K. (2010). UK Royal Navy Marine Mammal Observations. Data downloaded from OBIS-SEAMAP (http://seamap.env.duke.edu/dataset/64) on yyyy-mm-dd.

NIWA (2015). Antarctic Biodiversity Studies 2006 - Ross Sea, Scott Island, and Balleny Islands (TAN0602). Southwestern Pacific OBIS, National Institute of Water and Atmospheric Research, Wellington, New Zealand, 1061 records, Online http://nzobisipt.niwa.co.nz/resource.do?r=tan0602 released on April 17, 2015. https://doi.org/10.15468/9jchw1 accessed via GBIF.org on 2021-02-11.

Peat, H., (2020). British Antarctic Survey Argos satellite tracking data. Data downloaded from OBIS-SEAMAP (http://seamap.env.duke.edu/dataset/103152294) on 2021-02-09 and originated from OBIS (https://obis.org/dataset/528fe00d-8ca0-4c32-b6b2-fe72b05d9a6e)

Pirotta, V., (2020). RV Investigator Voyage IN2017_V01 Whale Observations, Sabrina coast, Antarctica (2017). Data downloaded from OBIS-SEAMAP (http://seamap.env.duke.edu/dataset/103152433) on 2021-02-10 and originated from OBIS (https://obis.org/dataset/53f0f94d-2343-461c-b732-8d8c1b8379b2)

Raymond, B., and Kool, J. (2020a). Cetacean Sightings Survey and Southern Ocean cetacean program. Australian Antarctic Data Centre. Occurrence dataset https://doi.org/10.15468/i5bfbf. Data downloaded on 2021-01-08

Raymond, B., and Kool, J. (2020b). APIS - Antarctic Pack Ice Seals 1994-1999, plus historical data from the 1980s. Australian Antarctic Data Centre. Occurrence dataset https://doi.org/10.15468/5j6flc

Raymond, B., and Watts., D., (2020). Seabirds of the Southern and South Indian Ocean. Data downloaded from OBIS-SEAMAP (http://seamap.env.duke.edu/dataset/103150014) on 2021-02-10 and originated from OBIS (https://obis.org/dataset/e62bd21e-63ff-41d7-a656-f765816e2800)

Rogers, T.L., Ciaglia, M.B., Klinck, H. and Southwell, C., (2013). Density can be misleading for low-density species: benefits of passive acoustic monitoring. PLoS One, 8(1), p.e52542. https://doi.org/10.1371/journal.pone.0052542

Rogers, T., and Hogg, C. (2018). Leopard and Weddell seal program 1999/2002. Australian Antarctic Data Centre. Occurrence dataset https://doi.org/10.4225/15/54d05d0cc8f50

Ropert-Coudert, Y., Van de Putte, A.P., Bornemann, H., Charrassin, J., Costa, D.P., Danis, B., Hückstädt, L.A., Jonsen, I.D., Lea, M., Reisinger, R.R., Thompson, D., Torres, L.G., Trathan, P.N., Wotherspoon, S., Ainley, D.G., Alderman, R., Andrews-Goff, V., Arthur, B., Ballard, G., Bengtson, J., Bester, M.N., Boehme, L., Bost, C., Boveng, P., Cleeland, J., Constantine, R., Crawford, R.J.M., Dalla Rosa, L., de Bruyn, P.N., Delord, K., Descamps, S., Double, M., Emmerson, L., Fedak, M., Friedlander, A., Gales, N., Goebel, M., Goetz, K.T., Guinet, C., Goldsworthy, S.D., Harcourt, R., Hinke, J., Jerosch, K., Kato, A., Kerry, K.R., Kirkwood, R., Kooyma, G.L., Kovacs, K.M., Lawton, K., Lowther, A.D., Lydersen, C., Lyver, P.O., Makhado, A.B., Márquez, M.E.I., McDonald, B., McMahon, C., Muelbert, M., Nachtsheim, D., Nicholls, K.W., Nordøy, E.S., Olmastroni, S., Phillips, R.A., Pistorius, P., Plötz, J., Pütz, K., Ratcliffe, N., Ryan, P.G., Santos, M., Schytte Blix, A., Southwell, C., Staniland, I., Takahashi, A., Tarroux, A., Trivelpiece, W., Wakefield, E., Weimerskirch, H., Wienecke, B., Xavier, J.C., Raymond, B., Hindell, M.A. (2020): The Retrospective Analysis of Antarctic Tracking (Standardised) Data from the Scientific Committee on Antarctic Research. v1.3. SCAR - AntOBIS. Dataset/Metadata. https://ipt.biodiversity.aq/resource?r=raatd_scar_trackingdata&v=1.3 https://doi.org/10.4225/15/5afcb927e8162 accessed via GBIF.org on 2021-05-03.

Scheidat, M. and Herr, H. (2018): Aerial cetacean survey Southern Ocean 2006/2007. PANGAEA, https://doi.org/10.1594/PANGAEA.894937

Scheidat, M., Herr, H., and Siebert, U. (2018): Aerial cetacean survey Southern Ocean 2008/2009. PANGAEA, https://doi.org/10.1594/PANGAEA.894936

Schmitt, N., Polanowski, A., and Connell, D. (2018). Patterns of population genetic structure among Australian and South Pacific humpback whales 2007/11. Australian Antarctic Data Centre. Occurrence dataset https://doi.org/10.15468/7e1mdj. Data downloaded on 2021-01-08

Shabangu, F. W., and Rogers, T. L. (2021). Summer circumpolar acoustic occurrence and call rates of Ross (Ommatophoca rossii) and leopard (Hydrurga leptonyx) seals in the Southern Ocean, Dryad, Dataset, https://doi.org/10.5061/dryad.rr4xgxd79 Data downloaded on 2021-02-01

Southwestern Pacific OBIS (2014a). British Antarctic (Terra Nova) Expedition, 1910-1913. Southwestern Pacific OBIS, National Institute of Water and Atmospheric Research (NIWA), Wellington, New Zealand, 1779 records, Online http://nzobisipt.niwa.co.nz/resource.do?r=terranova released on July 29, 2014

Southwestern Pacific OBIS (2014b). Biological observations from the Discovery Investigations 1925-1935. Southwestern Pacific OBIS, National Institute of Water and Atmospheric Research (NIWA), Wellington, New Zealand, 33337 records, Online http://nzobisipt.niwa.co.nz/resource.do?r=discovery_reports released on January 23, 2015.

SWPRON (2019): Biological records from the U.S Antarctic Service Expedition, 1939-41. v1.1. Southwestern Pacific Ocean Biogeographic Information System (OBIS) Node. Dataset/Occurrence. https://nzobisipt.niwa.co.nz/resource?r=usase&v=1.1

Treasure, A.M., Roquet, F., Ansorge, I. J., Bester, M. N., Boehme, L., Bornemann, H., Charrassin, J.-B., Chevallier, D., Costa, D. P., Fedak, M. A., Guinet, C., Hammill, M. O., Harcourt, R. G., Hindell, M. A., Kovacs, K.M., Lea, M.-A., Lovell, P., Lowther, A. D., Lydersen, C., McIntyre, T., McMahon, C. R., Muelbert, M. M. C., Nicholls, K., Picard, B., Reverdin, G., Trites, A. W., Williams, G. D., and de Bruyn, P. J. N., (2017). Marine Mammals Exploring the Oceans Pole to Pole: A review of the MEOP consortium. Oceanography 30(2):132–138, doi: 10.5670/oceanog.2017.234.

Vishnyakova, K., (2016): Antarctic whale observation on a platform of opportunity abroad krill fishing vessel "Dalmor II", April - July 2011.. v1.9. Ukrainian Scientific Centre of Ecology of the Sea (UkrSCES). Dataset/Occurrence. http://gp.sea.gov.ua:8082/ipt/resource?r=whale_observation_ccamlr_ukrsces&v=1.9

Watts, D., (2009) Whale log - observations from ANARE voyages , Australian Antarctic Data Centre - CAASM Metadata (http://data.aad.gov.au/aadc/metadata/)

Watts, D., (2020b). Whale Observations from the British, Australian and New Zealand Antarctic Research Expedition (BANZARE) voyages 1929-30 and 1930-31. Data downloaded from OBIS-SEAMAP (http://seamap.env.duke.edu/dataset/103150599) on 2021-02-09 and originated from OBIS (https://obis.org/dataset/6e8bfa14-eabf-4295-8e56-cbf851edd391)

Wege, Mia; Bornemann, Horst; Biddle, Louise C; Blix, Arnoldus Schytte; Lübcker, Nico; Nordøy, Erling S; Postma, Martin; Bester, Marthán N (eds.) (2021): Ross seal tracking data from expeditions SCALE (MV SA Agulhas II, 2019), PS111 (RV Polarstern, 2018) and S55 (MV SA Agulhas II, 2016). PANGAEA, https://doi.org/10.1594/PANGAEA.929949

Williams, R., Hedley, S.L. and Hammond, P. L., (2006) Modeling distribution and abundance of antarctic baleen whales using ships of opportunity. Ecology and Society 11(1): 1.

C Annex 3 – Behavioural responses of Antarctic marine mammals to anthropogenic noise: A review of relevant literature to facilitate noise threshold determinations

Authors: Nowacek, D. P., Friedlaender, A. S., Janik, V. M. & Southall, B. L.

Human activity in the waters of the Southern Ocean, including the Antarctic coastal waters, is likely to increase in the coming years and decades; this activity also has the potential to disturb the mammals that inhabit these areas. The specific types of activities of interest for this study are those that generate acoustic energy in the marine environment. We will use the term 'noise' in our discussions, which can and does have negative connotations, as this acoustic energy is unlikely to have any beneficial effects for these animals. We will be considering the following anthropogenic sources of noise: i) vessels; ii) seismic air guns; and iii) hydroacoustic research equipment. With respect to the species of interest for this study, we will consider those listed in Erbe et al. (2019).

This study is not intended to make a case for nor recommend specific noise thresholds for individual species and their responses to specific noise sources. Instead, it is constructed to inform an expert elicitation (EE) process that will determine those noise thresholds for behavioural responses. So, to provide the necessary information for the expert elicitation process, this study presents:

1. An overview of behavioural response studies (both controlled exposure experiments and observational efforts) and their results related to marine mammals and noise sources considered in this study based on relevant literature;
2. A list of and discussion on the potential factors that may influence and explain the response of Antarctic species on the exposure to noise; and
3. A proposed severity scale for ranking observed behavioural responses of free-ranging marine mammals in this study to various types of noise as emitted by the noise sources considered in this study.

We have listed all of the studies we found during our research in Annex 3, Supplement A, B and C, and they are organized by sound source type. The color coding in the spreadsheets in this supplement indicate whether they were scored and, if scored, how the studies were scored, e.g., whether the full severity scoring system was used or whether a reduced protocol was followed (described below). Not all the studies were scored, and the reasons for not scoring all of them include i) too many to systematically score; and, as importantly, ii) many/most do not contain sufficient information/detail to be fully scored. We selected studies that we thought would be the most useful for the EE process and that had sufficient information to be scored with either the full or reduced protocols. For all reduced score studies, we have provided a paragraph of text summarizing the study and any responses, or lack thereof. In the conclusions/recommendations section, we provide our summary of our review and, further, a 'guide' for the EE workshop that leads the participants through how and why we assembled the materials we have done for that process.

C.1 Species considered

As mentioned above, we have taken as our species for consideration to be the list of species included in the recent paper by Erbe and colleagues (2019) and included here as Table C. 1. Generally, these are species of marine mammals that occur in Antarctic waters, or at least in the waters of the Southern Ocean, though not necessarily in Antarctic coastal waters, e.g., spectacled porpoise, *Phocoena dioptrica*. Importantly, and not surprisingly, there are not published studies for behavioural responses of all species listed in Erbe et al. (2019) exposed to the three noise sources. We have used the available literature where possible, where none exists we have reviewed literature for species as closely related as possible. This issue is discussed further below, but as the pinniped species and one cetacean occur only in Antarctica and, in the case of the pinnipeds, many do not have relatives outside of Antarctica, even at the genus level. For example, while we know a bit about the ecology (Krause et al. 2015) and acoustic behaviour (Cato and Rogers 2002) of leopard seals (*Hydrurga leptonyx*), we were unable to find a single study that considered their response to any of the noise sources of interest. As such, the leopard seal represents quite a difficult species in the current review given this paucity of knowledge. While they are relatively closely related to some other Antarctic species (e.g., crabeater seal) and they are in the same functional hearing group (see Southall et al. 2019), their ecology as a top predator is radically different from crabeater or Weddell seals, so extrapolating the limited data we have on phocid seals is arguably problematic.

Overall, given issues like the leopard seal just discussed, we have followed a general philosophy in choosing papers to review. First, if studies documenting the responses of a particular Antarctic species in Antarctic waters do not exist, we have reviewed studies of that species from different parts of the world, but only if they are engaged in the same behavior (e.g., feeding) as we would expect in Antarctica. For example, there are many studies of humpback whales and their responses to both seismic air guns and vessels. However, some of those studies were done on the calving/mating grounds, so we would not consider those relevant because, while humpbacks have been recorded singing in Antarctica (Stimpert et al. 2012), the calving/mating behavior in areas like Hawaii has not been observed so then we consider the context of exposure to be different enough so as to be misleading in terms of understanding the potential for disturbance. Secondly, if there are no studies at all reporting responses for a particular species, we have tried to generalize and extrapolate results from related species, but even this has limitations, e.g., as noted above, we have not found any studies reporting behavioral responses of any Antarctic phocid species to hydroacoustic research sources, so we have included a study of grey seals to high frequency sonar (Hastie et al. 2014).

C.2 Hearing sensitivity of reviewed species

One of the primary considerations when contemplating the potential for impact of some anthropogenic sound is the sensitivity of the individual species with respect to the sounds themselves, e.g., frequency spectrum, received levels. In other words, to respond behaviourally to a sound, the animal must be capable of sensing that sound (e.g., the auditory system responds to the given frequency), and, if it is, that the sound must be received at a level that is perceptible. These may seem rather straightforward questions to be answered, but in the case of marine mammals there are many species for which they remain open. Southall et al. (2019) provide the latest and most comprehensive review of hearing capabilities, and provide the functional hearing groups for the species listed in Erbe et al. (2019) that are the focus of this review (Table C. 1). It is important to note here that no empirical data exist for the hearing sensitivities in any mysticete cetacean, and Southall et al. (2019) do give 'hearing curves' for these species but acknowledge that they are imperfect. Secondly, having the hearing capabilities, including weighting functions, at hand is important for this review so they can be easily compared with the characteristics (e.g., level, frequency range, impulsivity) of the sources we include in our review; the nature of the sounds when they are received is also of obvious importance, and these characteristics can be obtained through measurement or modelling. As a straightforward example, based on this latest information described in Southall et al. (2019), we would not expect a humpback whale to respond to a hydroacoustic source that produces sound at 200 kHz. However, we note that even if an acoustic source is specified to produce a given frequency, it is often true that many other frequencies are produced, e.g., side lobes of the signal. As an example, Deng et al. (2014) documented evidence of frequency spreading in several hydroacoustics systems, showing that despite the sonar being reported to operate at 200 kHz, there was noticeable energy at 90 kHz. So, the full specifications and/or direct measurements of acoustic sources should be considered when exploring overlaps between anthropogenic noise sources and marine mammal hearing abilities.

Not only do Southall et al. (2019) provide functional hearing groups for all marine mammals, but they also give critical pieces of information such as the inflection points and slope for the high and low frequency roll-offs (see equation 1 in Southall et al. 2019), i.e., how quickly does an animal's sensitivity decrease from the point of best hearing. This information is critical for estimating the sensitivity of individual animals to a particular sound in a particular situation, e.g., would we expect a porpoise 1000 m from a multi-beam sonar to be able to detect the signal. Answering such a question requires the auditory system information such as that provided in Southall et al. (2019) taken together with the amplitude of the source, the propagation loss, other propagation effects on the signal, and the ambient noise level(s) at the frequency(ies) of interest. These latter quantities can be measured and/or modelled, and, when those steps are done, an informed estimate of the animal's ability to detect and perceive the sound is possible. Whether the animal displays some behavioural response is a wholly separate question, but to inform the EE process, the possibility of responding behaviourally is only triggered if the sound can be sensed by the animal. So, though we are providing only a review of the documented behavioural responses (or lack thereof), we believe it is vitally important to include this discussion of hearing abilities, particularly since at least part of this review will have to consider proxy species for the Antarctic species of concern as little or no data exist for behavioural responses for several of them.

Table C. 1: Focal species included in literature searches and review, and their functional hearing groups. *Hearing groups as defined by Southall et al. (2019).

Species group	Species	Latin name	Functional hearing group*
Mysticete	Dwarf Minke whale	*Balaenoptera acutorostrata*	LF
Mysticete	Antarctic Minke whale	*Balaenoptera bonaerensis*	LF
Mysticete	Sei whale	*Balaenoptera borealis*	LF
Mysticete	Pygmy blue whale	*Balaenoptera musculus brevicauda*	LF
Mysticete	Antarctic blue whale	Balaenoptera musculus intermedia	LF
Mysticete	Fin whale	*Balaenoptera physalus*	LF
Mysticete	Southern right whale	*Eubalaena australis*	LF

Species group	**Species**	**Latin name**	**Functional hearing group***
Mysticete	Humpback whale	*Megaptera novaeangliae*	LF
Odontocete	Arnoux's beaked whale	*Berardius arnuxii*	HF
Odontocete	Long-finned pilot whale	*Globicephala melas*	HF
Odontocete	Southern bottlenose whale	*Hyperoodon planifrons*	HF
Odontocete	Hourglass dolphin	*Lagenorhynchus cruciger*	VHF
Odontocete	Gray's beaked whale	*Mesoplodon gray*	HF
Odontocete	Strap-toothed whale	*Mesoplodon layardii*	HF
Odontocete	Killer whale	*Orcinus orca*	HF
Odontocete	Spectacled porpoise	*Phocoena dioptrica*	VHF
Odontocete	Sperm whale	*Physeter macrocephalus*	HF
Odontocete	Cuvier's beaked whale	*Ziphius cavirostris*	HF
Pinniped	Antarctic fur seal	*Arctocephalus gazella*	OCW/OCA
Pinniped	Leopard seal	*Hydrurga leptonyx*	PCW/PCA
Pinniped	Weddell seal	*Leptonychotes weddellii*	PCW/PCA
Pinniped	Crabeater seal	*Lobodon carcinophaga*	PCW/PCA
Pinniped	Southern elephant seal	*Mirounga leonina*	PCW/PCA
Pinniped	Ross seal	*Ommatophoca rossii*	PCW/PCA

C.3 Review of studies

C.3.1 Types of studies considered

Two primary experimental designs have been used to assess the responses of marine mammals to noise: controlled exposure experiments and observational studies. Both methods have their strengths and weaknesses and can be considered quite complementary as, to a certain extent, one has strengths where the other has weaknesses and vice-versa.

C.3.2 Controlled exposure experiments

Controlled exposure experiments (CEEs), also sometimes referred to as ‘playback studies’, consist of discrete exposure events where the researchers are in control of the source. In so doing, the researchers control the timing (e.g., exposing whales at the surface vs. on a dive), the signal (e.g., short frequency sweeps that mimic a multi-beam signal), and the amplitude. By controlling the source, the researchers can also heavily influence which animals are exposed and, in many cases, collect baseline or ‘before’ data so as to have some amount of control data against which to compare the ‘exposed’ or ‘during’ period. Collecting such baseline data is not unique to these studies, but knowing where and when the exposure will occur facilitates the systematic collection of such data. Additionally, CEEs often include the attachment of biologging devices to at least some of the exposed animals, and these devices dramatically increase the data available to the researchers as they attempt to determine if and how the animals respond. Again, such devices are not unique to CEEs, but with control of the source the researchers can direct exposure to tagged individuals. So, CEEs confer significant experimental advantages for the researchers in terms of the amount and type of data collected, including the ability to conduct actual experimental controls, i.e., creating the full exposure scenario without actually projecting the sound, which allows for understanding other impacts the researchers might have, e.g., presence of research vessels.

CEEs do come with the caveat that the sample sizes can be small relative to other experimental models (see below), and, as mentioned above, such shortcomings can dovetail advantageously with other experimental models, including the fact that CEEs can and do provide details of exposure and response that can be applied more broadly in other models, e.g., observational studies.

C.3.3 Observational studies

Observational studies are generally considered to be those where the researchers make opportunistic observations upon the exposure of animal(s) to some noise source. Like CEEs, observational studies have benefits as well as drawbacks in informing our understanding of the behavioural response of marine mammals to noise. In general, observational studies result in larger sample sizes and thus have the potential to sample more contexts. These larger samples, however, usually come at the expense of details about the exposure as well as the animals’ responses. Without control of the sound source, the researchers rely on opportunistic exposures so they cannot, for example, provide appropriate experimental controls nor usually obtain detailed data of exposure. Data collection during observational studies can be conducted in the same ways as CEEs, e.g., tagging individuals, but without control of the sound source the exposure may or may not happen. Researchers have made use of tags with longer attachment times to try to sample animals during exposure. Observational studies of exposure using passive acoustic monitoring (PAM) have become popular (e.g., Cerchio et al. 2014) as the technique allows for long sampling windows. These studies can cover large areas and sample many individuals, but do have specific and sometimes significant limitations, e.g., if animal vocalizations cease in an area where a noise source occurred, was it because the animals stopped vocalization or because they left the area. Improved statistical methods have increased applications, including another complementary application of different study types, namely obtaining vocalization rates obtained during tagging and CEEs that can then be applied in statistical models to probe the larger PAM data sets. We are not advocating one type of study over another, indeed CEEs and observational studies can and have been used in quite complementary and synergistic ways, and the larger assessment of behavioural responses to develop exposure thresholds can and should use results from both.

The last issue we wish to raise in the context of study types is the use of behavioural data collected on individual animals vs. groups of animals. Long-term records of individual animal behaviour (i.e., sampling all behavioural states and events via focal-animal sampling, *sensu* Altmann 1974) are the ideal and most thorough way to assess whether an observed behaviour falls in or out of the normal repertoire or severity and thus represents a disturbance. Long-term records of individuals are very difficult to obtain, particularly for marine mammals, which are out of our sight for much of the time. Tagging data have been used very effectively to sample behaviour during experiments (e.g., Miller et al. 2009), but tags come with caveats, e.g., short time periods sampled and/or course level of sampling, the procedure of tagging and the tag itself (Miller et al. 2009; Winsor et al. 2017). Behavioural observations from vessels have also been used successfully in studies of disturbance (Miller et al. 2012), though they of course have caveats as well, e.g., inability to track individuals for long periods; sampling protocols can be developed to effectively sample groups of animals can be used to balance some of these shortcomings (Altmann, 1974; Miller et al. 2012).

Regardless of the type of study, there are also different ways in which the data from a given study are analyzed, specifically here with respect to individual vs. group analyses. That is to say, some studies use data collected on individual animals but, for good reason, use analytical techniques that consider all of the data together, i.e., with all individuals grouped together. For example, DeRuiter et al. (2017) use all of the dive data collected from several individuals to construct a very informative model of diving behavior for the species. The model results are very insightful and even show some response to the noise stimulus used. With the way we have constructed our review and indeed the exposure context matrix, it is difficult to consider this as more than a sample size of n=1 if one is trying to assess the behavioural response of these animals to the noise stimulus in order to create thresholds. If the exposure and response were recorded for each individual in the study, then even if (as one would expect) the animals responded differentially based on received level or some other exposure context, we could still use those differential responses to create a function that captured those responses and also gave us more power to assess the risk of exposure and/or create acceptable exposure thresholds.

C.4 Review of Studies – scoring and descriptions

Southall et al. (2007) developed an initial response severity scale and reviewed the existing literature for different sound types and marine mammal taxa and summarized the results scored by a subset of the authors and collectively agreed upon (adjudicated) by scorers. Their results failed to converge on a single ‘threshold’ for all responses and severities or even to suggest clear linear relationships in response severity scaled to exposure received noise level. However, several patterns did emerge in terms of overall responsiveness, e.g., some species consistently showing sensitivity (e.g., harbour porpoises) while others appear more tolerant (e.g., humpback whales). Further, even within some individual species (e.g., bowhead whales), context-specific differences in response emerged from the application of the Southall et al. (2007) severity scale relative to received level; individuals in certain behavioural stages (migrating) appeared more sensitive at lower received levels than individuals who were more tolerant in other behavioural states (feeding). The implication of these observations was that within certain taxa or where relevant contextual factors could be known and considered discretely, the probability and severity of response could be described probabilistically as a function of received level (and/or other factors). Thus, while Southall et al. (2007) failed to present a single unifying response 'threshold' or even risk probability function spanning all marine mammals and noise exposure types, they provided a descriptive foundation from which objective assessments of response severity could be based, as well as some early categorizations of potentially relevant species and behavioural state parameters for parsing observed results.

Several empirical studies of marine mammal behavioural responses to noise exposure have employed the Southall et al. (2007) severity scale to identify specific changes of assigned severity, including modifications and the use of expert reviewers (Miller et al. 2012; Southall et al. 2019b). Both Miller et al. (2012) and Southall et al. (2019b) yielded individual instances of known exposure and response within a time-series context where discrete exposures of determined (and variable) severity and corresponding exposure received level were known. Additional statistical methods have been developed and applied to integrate the results of such known responses (or lack thereof) in known exposure conditions to derive species-specific and multi-species exposure-response risk functions with model selection methods (Harris et al., 2016), Bayesian hierarchical models (e.g., Miller et al., 2014), and recurrent event survival analysis (Harris et al., 2015). These kinds of integrative analyses to yield predictive, probabilistic response functions for variable responses of specified severity are increasingly being applied in regulatory contexts and extended to assessing impacts on individual vital rates and consequences for population-level impacts. Specifically, modelling efforts to quantify population consequences of disturbance from noise seek to build from short-term behavioural and physiological changes to longer-term population level effects (e.g., Pirotta et al. 2018).

Ongoing efforts seek to parameterize such population-level modelled impacts with empirical data from behavioural responses measured in individuals and evaluated with response severity assessments using expert elicitation (e.g., Southall et al. 2019b). These kinds of integrative assessments coupling short and longer-term individual and population level responses inherently require information on the type, probability, and severity of responses. Further, they require information about how responses are manifest in the context of differing vital rates (e.g., foraging, reproduction, survival). Finally, they are informed and enhanced by empirical measures of response at both the individual and group/population level. Obtaining and evaluating results within systems from these different perspectives is increasingly relevant and needed for efforts to evaluate population-level impacts from discrete and aggregate stressors (National Academies, 2017; Pirotta et al. 2019).

Given these divergent areas of both progress and need since Southall et al. (2007), Southall et al. (In press) provide new and adapted methods for the assessment of behavioural response in the form of a completely new exposure matrices (Table C. 2) and severity scale (Table C. 3); we have adapted and applied these latest methods for our own review here. These assessment tools demand a substantial amount of information about the exposure events, and so we have segregated the studies we reviewed into those for which we can fully (or nearly) apply the exposure matrices and severity scores and those for which insufficient information exists to do so but are still useful.

A full application of the context and behavioural response severity matrices provided in Table C. 2 and Table C. 3 to the entirety of marine mammal literature on behavioural responses to the three types of noise in field contexts is well beyond the scope of this study, though we have assembled a comprehensive list of available studies. However, in an effort to evaluate and demonstrate how the modified severity assessments functioned, with multiple assessors, we sought to evaluate a sub-set of the existing literature, focusing of course on the species identified in Erbe et al. (2019) and, where possible, studies that were conducted in Antarctica. Where necessary, e.g., studies of seismic surveys, we used a structured process to select a manageable number from over 75 studies identified and considered. With other sources, e.g., hydroacoustics, very few studies were identified that looked at the effects of these sources. With respect to this source type, it is important to describe the discussion that occurred regarding the type of signal(s) considered relevant. Specifically, in their review of published studies, Erbe et al. (2019) included naval sonar as a source type, but it was determined that for the current review naval sonar would not be considered, given the quite different signals as well as how they are used when compared to hydroacoustic research sources. For example, mid-frequency active sonar (MFAS) as a naval source is very different when compared to a scientific echosounder or multi-beam mapping system. An exploration of the differences in these signals and the potential those differences have for affecting animals is beyond the scope of this report, but the decision was taken to not review studies of the effects of naval sonar and to focus only on true hydroacoustic research sources (Supplement 3C). We would like to offer, however, a few ways in which naval sonar signals are different to hydroacoustic research sources. First, the method of deployment of naval sonar can be quite different as, in the case of MFAS, the sonar transducer is swept through the area in front of the vessel instead of being in a fixed orientation as hydroacoustic sources usually are. Also, while naval sonar and hydroacoustic sources use similar frequencies, the structure of the signals is different, e.g., naval sonar signals often vary frequency modulated (FM) with continuous frequency (CF) signals to maximize their ability to detect, classify and track moving targets. Other differences exist, as do some similarities, but our recommendation would be that the EE process carefully consider the type and presentation of a signal when attempting to define acceptable exposure thresholds; targeted reviews of responses to specific signals can be done quite efficiently, with the recognition that studies of that particular signal type may or may not exist.

We opted to focus primarily on studies of free-ranging marine mammals using the field severity scale from Southall et al. (In press), given the larger prevalence of such studies in the published literature and the lack of captive studies focused on relevant species. Given the shortage of studies on hydroacoustic sources, however, we did include a study with a captive seal species (Hastie et al. 2014) so as to provide material for review. Finally, we considered all available published studies (through 2020) but reviewed them based on the criteria discussed above (e.g., relevant species and habitat(s)). The studies in each of the three source types that were chosen (Annex C3A, C3B and C3C) were fully assessed by four independent reviewers, specifically the authors of this section.

C.4.1 Studies for which severity scoring is possible

Full severity scoring was possible for a subset of the identified studies. The severity scoring exposure/context matrix includes a large and diverse amount of information, and collecting and providing all of this information can be challenging, especially in studies of wild marine mammals. That said, this information can be critical in understanding the effects observed or the lack thereof. The ideal scale for assessing impacts would involve quantitative scales of one or more parameters, and, if more than one parameter is estimated, there should be a clear basis for the function using all of the parameters to generate a combined score. Focusing on the specifics of the problem at hand can make it possible to create one score to assess very different effects. Southall et al. (2007) developed such a severity scale by categorically describing mammal behavioural responses to noise in ascending order of presumed consequence. For example, responses such as a ‘brief orientation’ to a noise source were deemed to be low severity (severity score: 1) whereas more intense or sustained responses such as ‘prolonged changes in locomotion’ (score: 5) and ‘significant separation of females and dependent offspring’ (score: 8) were deemed to represent moderate and high severity responses, respectively. Such ordinal scores were assigned within the context of an experimental or observational noise exposure event by an informed observer or group of observers based on the extent to which the observed behaviour matched the described responses in the severity scoring table. Further, Southall et al. (2007) recommended coalescing severity scores in the 0-3, 4-6, and 7-9 categories respectively into ‘low’, ‘moderate’, and ‘high’ severity responses. Despite the quite different contexts represented in field and laboratory conditions, a single ordinal scoring table was proposed though with separate columns considering typical kinds of responses observed in free-ranging and captive marine mammals, respectively. In the updated assessment of the severity of marine mammal behavioural responses to anthropogenic noise, Southall et al. (2021) constructed a matrix to capture the contextual variables of exposure (Table C. 2) and a response severity score matrix (Table C. 3). The severity scoring matrix is quite different than the 2007 version in as much as it considers the responses in the context of important life functions: survival, feeding, and reproduction. For each of these categories it assigns an ordinal score (0-9) for specific behaviours (e.g., cessation of vocal behaviour) in order to assist in assessing the severity of responses, with a score of ‘9’ indicating the most severe responses, e.g., stranding.

The full suite of information for all of the studies we reviewed with full severity scoring is shown in Annex C3A, C3B and C3C, including whether any response(s) were observed and, if so, the score(s) for the response(s). While there are still missing pieces of information for most of these studies, having the information organized in this way will hopefully provide the distilled and refined information needed for the process of deciding on acceptable thresholds.

Table C. 2: Subject-specific (A), contextual (B), and exposure metrics (C) reviewed in reviewed studies of marine mammal behavioral responses to noise. Adapted from Southall et al. (2021).

A. SUBJECT-SPECIFIC (Individual or Group) VARIABLES										
SPECIES	FUNCTIONAL HEARING GROUP	SUBJECT INDIVIDUAL IDENTIFIER (where applicable)	SUBJECT WEIGHTING (subject A for stimulus B for N times divide run by N)	CENSORED DATA? (No or L/R if Yes)	AGE CLASS (if known)	SEX (if known)	CALF PRESENT? (if female)	GROUP SIZE (single or best estimate of social group size)	GROUP COMPOSITION (general sex/age structure)	BEHAVIORAL STATE (Deep/shallow feeding; slow/fast travel; social interaction; calling)

B. EXPOSURE CONTEXT VARIABLES										
EXPOSURE TYPE (start of exposure	SOURCE-ANIMAL RANGE (start of exposure)	SOURCE DEPTH (m)	ANIMAL DEPTH (m)	GENERAL SOURCE MOVEMENT (relative to subject)	NAVIGATIONAL CONSTRAINTS (is subject confined in any way?)	EXPOSURE NOVELTY (is source type common/rare for area)	EXPOSURE SIMILAR TO PREDATOR SOUNDS?	OTHER SPECIES PRESENT IN THE AREA?	PREDATOR SPECIES PRESENT IN THE AREA?	OTHER ANTHROPOGENIC PRESENCE/NOISE IN AREA? (type and proximity)

C. EXPOSURE METRICS												
CONTINUOUS OR INTERMITTENT EXPOSURE	INTERVAL BETWEEN EXPOSURES (s)	INDIVIDUAL TRANSMISSION DURATION	CONTINUOUS OR INTERMITTENT EXPOSURE	INTERVAL BETWEEN EXPOSURES (s)	ORDER IF MULTIPLE EXPOSURES (identify sequence/order)	HARMONICS PRESENT? (none, few, many)	RMS SPL @ change point or max if no change (Broadband and max 1/3rd-oct)	Peak-peak RL @ change or max if no change (broadband)	SEL @ change point or max if no change (Broadband and max 1/3rd-oct)	SELcum @ change point or max if no change (Broadband and max 1/3rd-oct)	Signal-Noise Ratio (SNR) @ change point or max if no change (max 1/3rd-oct)	Sensation level (SnL) @ change point or max if no change (max 1/3rd-oct)

Table C. 3: Severity scoring for behavioral responses of wild marine mammals responding to noise, following Southall et al. (2021).

Response Score[18]	Behavioral Changes Affecting Survival	Behavioral Changes Affecting Feeding	Behavioral Changes Affecting Reproduction
0	No response detected with methods sufficient to identify responses relevant to survival	No response detected with methods sufficient to identify responses relevant to feeding	No response detected with methods sufficient to identify responses relevant to reproduction
1	Identifiable change in behavior indicating vigilance response: • Orientation • Interruption of resting behavior • Listening: delay in vocal behavior/locomotion/breathing • Detectable change in diving behavior • Minor deviation from typical migratory pathway	Detectable interruption of foraging behavior	Detectable interruption of advertisement and courtship behavior
2	Sustained or multiple vigilance responses		
3	• Individual investigation of potential threat • Recruitment of orienting behavior • Increase in contact or alarm calls to initiate social cohesion • Individual startle response	Behavioral state changes from foraging to other behavior	Behavioral state changes from advertisement and courtship to other behavior
4	• Prolonged silencing or other cryptic behavior to avoid detection • Defensive bradycardia or stillness • Increased interval between surfacing bouts • Reduction in variance of heading • Change in group cohesion • Brief/minor changes in vocal rates or signal characteristics - potentially related to higher auditory masking potential	• Non-foraging state longer than typical • Detectable elevation in energy expenditure (e.g., increase in dynamic acceleration, respiration rate, locomotion, speed) • Brief/minor changes in vocal rates or signal characteristics - potentially related to higher auditory masking potential	• Non-reproductive (advertisement and courtship) state longer than typical • Brief/minor changes in vocal rates or signal characteristics - potentially related to higher auditory masking potential
5	• Onset of avoidance behavior (e.g., heading away and/or increasing range from source)	• Reduction of foraging success less than typical daily intake	

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[18] Ordinal score of behavioral response severity for corresponding behaviors; responses identified for each ordinal score are not necessarily equivalent across conditions.

Response Score[18]	Behavioral Changes Affecting Survival	Behavioral Changes Affecting Feeding	Behavioral Changes Affecting Reproduction
	• Recruitment of defensive social behaviors (e.g., rafting, marguerite, vocal threats) • Increase in mother-offspring cohesion (including acoustic signaling and/or mother herding offspring)	requirement (during exposure period) • Detectable change in nursing behavior	
6	• Repeated startle response, abrupt agonistic behaviors (e.g., head thrusting, mouth gaping) • Individual aggressive behavior (e.g., jaw clapping, gnashing teeth, abrupt directed (rush/ramming) movement potentially directed at conspecifics) • Sustained avoidance behavior (e.g., heading away and/or increasing range from source) • Separation of females, dependent offspring exceeding baseline • Group aggressive behavior (e.g., mobbing) • Sustained changes in vocal rates or signal characteristics - potentially related to higher auditory masking potential	• Reduction of foraging success exceeding typical daily intake requirement (potentially extending beyond exposure period) • Energy expenditure exceeds nominal daily baseline • Sustained disruption of nursing behavior • Sustained changes in vocal rates or signal characteristics - potentially related to higher auditory masking potential	• Reduction of advertisement and courtship behaviors potentially sufficient to reduce reproductive success • Disruption of parental attendance behavior • Sustained changes in vocal rates or signal characteristics - potentially related to higher auditory masking potential
7	• Separation of females and dependent offspring sustained for long enough to compromise reunion • Clear anti-predator response (e.g., severe and/or sustained avoidance or aggressive behavior) • Displacement to area of increased predation risk • Failure of vocal mechanisms to compensate for noise (e.g., silencing affects group cohesion/defense)	• Reduction of foraging success sufficient to compromise health and/or reproduction • Failure of vocal mechanisms to compensate for noise (e.g., cessation of acoustically-mediated foraging)	• Interruption of breeding behavior • Failure of vocal mechanisms to compensate for noise (e.g., cessation of acoustic advertisement displays)
8	• Disruption of group social structure (breaking pair bonds/alliances, altering dominance structure) • Prolonged/significant separation of females and dependent offspring with	• Prolonged displacement to sub-optimal foraging habitat • Disruption of group social structure (cooperative feeding groups with	• Disruption of breeding behavior sufficient to compromise reproductive success (e.g., repeated interruption of mating, disrupting male-female association)

Response Score[18]	Behavioral Changes Affecting Survival	Behavioral Changes Affecting Feeding	Behavioral Changes Affecting Reproduction
	disruption of acoustic reunion mechanisms	specialized knowledge or division of labor)	• Disruption of group social structure (breaking pair bonds/alliances, altering dominance structure)
9	• Risk that behavioral response leads to serious injury or mortality (predation, outright panic, flight, stampede, stranding, mother-offspring separation)	• Disruption of energetic balance sufficient to result in morbidity or mortality	• Failure to successfully reproduce during breeding season

C.4.2 Studies for which only reduced severity scoring is possible

Many important studies of the effects of noise on marine mammals have been conducted that are not focused on measuring the detailed, individual animal responses and, importantly, the details of exposure and context for individual animals on relatively short time scales (e.g., over the course of an experiment). Instead, while these studies do focus on measurable parameters (e.g., clicking or singing rates), they are not necessarily attributable to individual animals and they often operate over longer time scales, including measuring possible population-level changes (e.g., shifting distribution) over months, seasons, or years. These studies provide key data on these broader-scale and longer-term perspectives that have direct relevance to population-level assessments, but they do not lend themselves to detailed assessments of behavioural changes as they relate to specific exposure levels and contexts. We acknowledge that it is challenging to evaluate such studies using the acute exposure, contextual parameters, and known individual response assessment called for in the severity scales that we have presented (*sensu* Southall et al. In press). Further, the practical outcome of the approaches taken in the acute, trackable exposure assessments described above can have unintended and, in some ways, unbalanced outcomes. For instance, a study that has a dozen well-defined individual exposure-response scored may effectively be weighting 12 times greater in a subsequent meta-analysis to derive response functions than a population-level study where many individuals are evaluated collectively. One ramification of the different focus of these studies is that the severity scale scoring we have developed cannot be applied directly to the behavioural changes observed because individual animals have not, for the most part, been directly observed. So, for these 'reduced-severity scored' studies for which it is not possible to glean the key details of exposure (e.g., individual animal exposure) or context, we believe it will be most beneficial for the EE process to provide a different and complimentary, albeit reduced, set of information and review; the report includes such information and reviews of key studies of both types. We present, in short narrative form, the information we have harvested from these reduced-scored studies including:

1. Type of methods used (e.g., experimental, historical data, modelling)
2. Type(s) of effects reported, both short term (e.g., behavioural changes, loss of acoustic space, click/buzz detection rates, social sound rates) and long term (e.g., health, distribution, reproductive/survival rates)
3. Type(s) of exposure (e.g., seismic, vessel, echosounder)

4. Estimated exposure levels (e.g., range(s) of possible sound pressure levels (SPL)/sound exposure level (SEL) [measured or modelled] based on distances between animals and sources)
5. Lessons learnt

We have included these studies in Annex C3A, C3B and C3C so that reviewers can see all of the information that was available, but we do not provide severity scores for the reasons already discussed. We provide these short narratives here:

Harris et al. (2001, airguns, seals) investigated the distance and behaviour of what was primarily ringed seals seen from a survey vessel towing an 11 airgun array in which all airguns fired simultaneously in the Alaskan Beaufort Sea. They compared 333 h of full array operation with times when only one airgun (105 h) or no airguns (300 h) were being used. The number of seals detected did not change across conditions, but the mean distance at which seals were seen from the vessel increased from 144 m with no airgun sounds to 234 m when the full array was operating. The broadband received SPL at 144 m was above 190 dB re 1 µPa. The authors concluded that the animals only showed a mild avoidance response at such levels since the distance they moved would only decrease the received level by around 3 dB. Based on surface observations, the animals appeared to stay within 500 m of the vessel even during full operations. Apart from increased swimming away from the vessel at full operation, no clear change in other surface behaviours was observed.

Castellote et al. (2012, vessels & airguns, baleen whale) assessed fin whales exposed to differing levels of vessel noise and seismic surveys. The whales changed their vocal behaviour in the louder vessel noise environments. In response to the seismic surveys, the authors conclude that the whales moved substantial distances to sing in a lower noise environment, and this conclusion is supported by the fact that the whales returned to original singing location when seismic survey ended. This result does call into question the often-cited conclusion that displacement to a different location is inconsequential, i.e., the singing location was important enough for the whales to move back once the noise source ceased. No information is available for actual exposure levels, but the SPL in the relevant frequency band increased by 13 dB to 116.7 re 1µPa, which indicates that the survey was 10s to 100s of kilometers distant from the whales.

Cerchio et al. (2014, aiguns, baleen whale) assessed 3096 individual data points representing 10-minute periods with an unknown number of humpback whales singing, with seismic pulses present in 449 of them. The authors report having documented a change in acoustic behaviour as the number of singers decreased by 0.03-0.08 per 10 dB increase received power spectral density in individual pulses.

Cholewiak et al. (2017, echosounder, beaked whale) reported numbers and click detections of beaked whales (*Ziphius cavirostris*, *Mesoplodon europaeus*, *M. mirus*, *M. bidens*) in the North-West Atlantic while operating a Simrad EK60 echosounder. This echosounder transmits a complex signal with energy between 18 and 200 kHz at an SPL @ 1 m over 240 dB re 1 µPa. The authors analysed 63 days of visual observations and 33 days of acoustic data. The echosounder was active for half of these days. The number of visual sightings did not differ between active and control days but of 118 beaked whale click detections, 96% occurred when the echosounder was not active. This suggests that beaked whales stopped clicking in reaction to the echosounder. However, clicks would be harder to detect in echosounder noise and it is unclear how that influenced the data.

Di Iorio & Clark (2010, seismic, baleen whale) monitored blue whale acoustic activity on 4 days with and 4 days without acoustic sparker explorations in the St Lawrence Estuary, Canada.

A seismic sparker works by discharging an electrical pulse between electrodes and a grounding point in seawater. This discharge creates an acoustic pulse, and the reflected signal is received by a hydrophone deployed at a set distance from the source. Sparker activity and whale calls were detected by passive acoustic recorders. Three to four whales were sighted per day on surveys conducted on the eight study days. Information on distance of sparkers to recorders were not available but the mean peak-to-peak sound pressure level at the recorders was 131 dB re 1 µPa(30–500 Hz) with a mean SEL of 114 dB re 1 µPa^{2}s. Sparkers were active for around 12 h per sparker day. The authors found that blue whale call rates more than doubled on days with sparker activity compared to quiet days and that blue whales called around three times as often during sparker activity when compared to quiet periods on the same days. They also detected increase calling rates in the first hour after the start of sparker noise compared to rates in the previous hour.

Holt et al. (2009, vessels, dolphin) analysed 104 killer whale calls from Puget Sound, WA, across 4 days and related the calculated source level of these calls to overall background noise levels. The main noise source in the area were other vessels. Background noise received levels between 1 and 40 kHz ranged from 98 to 123 dB re 1 µPa. Killer whale source levels ranged from 133 to 174 dB re 1 µPa. The authors reported that call source levels of call type S1 increased by 1 dB for each 1 dB increase in background noise levels. The 1-1 relationship reported by the authors was derived from a regression analysis.

Kates-Varghese et al. (2020, echosounder, beaked whale) used group vocalization periods (GVP) as a proxy for searching effort typically coincident with deep dives/feeding for Cuvier's beaked whales during exposure to a multi-beam echosounder. Little is known about the exposure experienced by the animals as the animals were only acoustically detected across a large navy training range in many groups, which probably were detected multiple times. The total source-on time was reported, but arguably this represents a sample of only 1, perhaps 2 across the two years. A response was detected as, while the animals did not avoid the area, they did change their vocal patterns, clicking more, so this would be scored as a brief/minor changes in vocal rates or signal characteristics, potentially related to higher auditory masking potential.

Risch et al. (2012, echosounder, baleen whale) compared humpback whale songs during the use of an acoustic, long-range mapping system with periods without the acoustic source. They measured exposure for ~1 hour/day for 11 days from the low frequency (0.4-1 kHz) frequency modulated pulses from Ocean Acoustic Waveguide Remote Sensing (OAWRS, Jagannathan et al. 2009) system to a singing humpback whale population. Even at long distances of ca. 200 km, the authors determined that humpback acoustic communication was affected by these signals with reductions in minutes per hour of song during exposure periods. The loudest received signal was at the lowest frequency (415 Hz centre frequency) and was 110 dB re 1 µPa; the levels for the higher frequency signals were lower though still above ambient. The signals emitted by the OAWRS system do, in some ways, resemble humpback signals, e.g., duration, frequency band, frequency modulation. It is unclear how the whales interpret these signals, and direct experimentation would likely be needed to investigate the parameters in the signals that could be causing the observed patterns. Of importance here is the spatial scale over which this effect was measured, though it must be interpreted with care as these were not controlled experiments.

Weir (2008, airguns, sperm whale, dolphin, baleen whale) observed sperm whales, humpback whales, and Atlantic spotted dolphins from a sighting survey vessel during a seismic survey. Some information about the source was reported, e.g., total exposure of 1313 hours, though no information about received levels or other acoustic parameters were reported. Weir reported no change in encounter rates during and outside of the seismic surveys for sperm or humpback whales, though encounters for Atlantic spotted dolphins were reportedly farther away during active seismic operations. Weir did report several anecdotal behavioural responses of individual animals, but no systematic responses were documented.

Williams et al (2014, vessel noise, dolphin) used historical data to probe for responses of killer whales to vessel noise, specifically they used theodolite tracks of killer whales and the presence/absence of vessels to look for effects, estimating the noise exposure level. We initially attempted to score this study (Annex C3B) and have included this attempt simply to illustrate how little information on individual animal exposure is included. The paper certainly contributes to our knowledge of, in this case, vessel noise exposure, finding that a minor change in respiration patterns occurred upon exposure to vessel noise. Importantly though, the authors also report that even at higher exposure levels there was no change in other parameters. This paper is also very interesting in that the authors used the Southall et al. (2007) severity scoring system (i.e., the older version), and they found that whether there was a significant change in behaviour was dependent on the assignment of the severity, in this case a ‘2’ vs. a ‘3’. One of the benefits of the new severity scoring system is that it removes the subjective assignment of severity, instead tying it to the objective observation of the behavioural change in the context of vital functions survival, reproduction, and foraging. Based on the position of the whales as determined by theodolite and the noise levels at those positions from sound transmission models, the authors estimated a broadband SPL of ca. 130 dB re 1µPa for the point at which they expected 50% of the whales to demonstrate behavioural responses when using a 2 on the Southall et al (2007) scale. When they used severity score of >3, the point at which >50% of whales were expected to respond was an estimated SPL of >150 dB re 1 µPa. This study is helpful as it was one of the early ones to incorporate a dose-response curve, and it also shows the limitations of the older severity scoring method.

Winsor et al. (2017, airguns, sperm whale) measured the spatial distribution of satellite-tagged sperm whales (*Physeter macrocephalus*) in proximity to seismic surveys in the Gulf of Mexico. The authors tracked 26 individuals, but given the nature of observations (e.g., often a single location during a specified survey), we considered it a group (single) observation. We considered scoring by individual and weighting by observations, but given the coarse nature of observations and lack of individual tracking we thought it most prudent to consider it a single observation. The range from the animal locations were specified in detail relative to known survey locations, but with tag location errors, which can be 10s to 1000s of meters, and the fact that locations are only measured when whales are at the surface, the actual distances between whales and survey vessels is only known with relatively poor accuracy. Recently, methods have been developed to take these same types of satellite-derived locations and create more accurate estimates of levels received at animal locations (Schick et al. 2019). The authors concluded that the positions of the whales were not affected by the seismic surveys, finding that locations were randomly distributed relative to vessel locations over 5-50 km ranges. Over such ranges and by aggregating the data across individuals, however, it is difficult to know if and how individual whales were affected, e.g., diving and foraging decisions, particularly as other studies have reported relationships between individual exposure and changes in foraging behaviour (Miller et al. 2009).

C.5 Conclusions and recommendations, e.g., in the context of determining exposure thresholds

Southall et al. (2007) compiled what most consider to be the first systematic approach to defining even initial noise exposure criteria, both for hearing injury as well as behaviour. In the almost 15 years since that initial attempt, we have certainly learned more about the behavioural responses of marine mammals to noise sources, but we have also learned more about the complexity underlying those responses and that they certainly cannot be predicted based on simple paradigms like step-function thresholds of received sound levels. Deterministic, single-value thresholds for broad taxa really do not exist, the responses of animals are probabilistic in nature, vary by taxonomic groups, and can be heavily influenced by contextual factors such as behavioural state. Whereas initial assessments and regulatory approaches focused almost entirely on received noise levels (in simple sound pressure units) with proposed step-function thresholds for very broad taxa, science is telling us loudly there is much more nuance required. Considerable variability in response type and magnitude has been observed for similar noise exposures as a function of species, age/sex class, individual behavioural state, and a host of interacting biological and ecological contextual factors (e.g., Richardson et al., 1990; Southall et al., 2007; 2019b; Ellison et al., 2012; National Academies, 2017). To be clear, there is no single response threshold (or even function) associated with a single aspect of noise exposure. However, this does not mean that logical, discernible relationships between key aspects of exposure and response cannot be scientifically derived and supported. We do not need to have, nor can we wait for, complete scientific understanding in these issues. Further, we should not strive to reflect the near-infinite complexity in these challenging and to some extent ephemeral issues with dozens or hundreds of exposure-response probabilistic functions for all species, age-classes, and individual behavioural states. We advocate here for a rational, common-sense framework with which to systematically and objectively assess available science and yield a manageable number of probabilistic response functions with which to make informed decisions, and we hope that our review has provided such a framework.

Our review began with the assumption that we would ‘score’ every reviewed paper, with scores being assigned to a variety of parameters (Table C. 2) culminating in the actual response score, if one was detected, according to the latest severity scoring efforts described in Southall et al. (In press). However, as Southall and co-authors (In press) discovered as well, many papers that explore behavioural responses to noise do not report many of the quantities that would, frankly, be helpful for understanding the context and severity of any responses observed. Certainly, in many cases, the information is not available or was not collected, but in some cases the information was simply not reported. In response to this limitation, we adapted our strategy so as to maximize the available information for this review of animals’ responses. Specifically, for a substantial subset of papers for which most of this contextual information was not available, we instead gathered what we could and then provided a written synopsis of the experiment and any results explicitly stated or that we could glean (i.e., ‘reduced severity scoring’). We struggle with quantification of responses themselves, perhaps even more so is quantifying the contextual variables, so we have attempted to combine the quantitative information that was reported with our descriptions and, to a limited extent, interpretations of the information in the papers.

We also recognize that there exists a continuum of strategies for managing exposure. The U.S. strategy of protecting individuals by dictating levels to which individual animals can be exposed, which some would argue is not the best for overall conservation, particularly given the complexity of the responses and the influence of contexts. However, by protecting vulnerable or particularly sensitive life history stages and/or species (e.g., mother-calf pairs, harbour porpoises) by limiting individual exposure certainly has value. In contrast, the EU strategy of protecting populations by adopting measures to reduce noise overall so as to reduce exposure to large numbers of animals is arguably better for conserving populations and is at the other end of the end of the continuum. This strategy fails, however, to consider particularly vulnerable groups or species and their exposure to isolated or transient noise events that may result in significant impacts. Regardless of overall strategy, there are benefits and challenges when trying to balance individual protection with population level consequences when anthropogenic ocean noise is being produced. We hope that our targeted review of behavioural responses will provide the information and framework for a constructive process to decide on acceptable exposure limits for Antarctic marine mammals.

D Annex 4 - Antarctic marine mammals and the issue of noise-induced threshold shift

Authors: Houser, D.

D.1 Introduction

The marine mammals of the Antarctic Ocean, south of 60° S, are composed of mysticete and odontocete cetaceans and phocid and otariid pinnipeds (Table D. 1). Most of the pinnipeds are tied to sea ice for the purposes of breeding and molting, with the exception of the Southern elephant seal (*Mirounga leonina*) and Antarctic fur seal (*Arctocephalus gazelle*), which use the pelagic waters of the Antarctic but typically breed and molt on land. Cetaceans using Antarctic waters include migratory species with seasonal presence and year-round inhabitants. Available information on the distribution and abundance of species has traditionally been limited to surveys during the austral summer, although passive acoustic monitoring methods are improving detections of Antarctic marine mammals during periods of dense sea ice coverage (e.g. Clark et al., 2009; Van Opzeeland et al., 2013; Van Opzeeland and Hillebrand, 2020). A recent review of potential noise impacts on marine mammals briefly summarizes what is known about Antarctic marine mammal distribution, abundance and trends (Table 2 of Erbe et al., 2019).

The Protocol on Environmental Protection to the Antarctic Treaty, or the Madrid Protocol, went into effect in 1998 and established the Antarctic as a natural reserve requiring human activities in the Antarctic to consider the protection of the environment. Annexes to the Protocol on Environmental Protection dictate that environmental impact assessments of proposed activities in the Antarctic be conducted prior to conducting any anthropogenic activities, and further contain regulations for protecting the flora and fauna of Antarctica. Noise due to human activities in the Southern Ocean has increased in the decades since the signing of the Antarctic Treaty, but no unified approach to assessing noise impacts to marine mammals exists under the treaty. Thus, member countries choosing to regulate ocean noise are required to establish criteria and exposure thresholds from which regulations are applied.

Table D. 1: Marine mammals of the Southern Ocean. The letters after each species name corresponds to the hearing group classification of Southall et al. (2019): LF – low frequency, HF – high frequency, VHF – very high frequency, PCW – phocid carnivores in water, OCW – other carnivores in water.

Species group	Family	Species
Mysticete	Balaenidae	Southern right whale (*Eubalaena australis* (LF))
Mysticete	Balaenopteridae	Dwarf minke whale (*Balaenoptera acutorostrota* (LF))
Mysticete	Balaenopteridae	Antarctic minke whale (*Balaenoptera bonaerensis* (LF))
Mysticete	Balaenopteridae	Sei whale (*Balaenoptera borealis* (LF))
Mysticete	Balaenopteridae	Pygmy blue whale (*Balaenoptera musculus brevicauda* (LF))

Species group	Family	Species
Mysticete	Balaenopteridae	Antarctic blue whale (*Balaenoptera musculus intermedia* (LF))
Mysticete	Balaenopteridae	Fin whale (*Balaenoptera physalus* (LF))
Mysticete	Balaenopteridae	Humpback whale (*Megaptera novaeangliae* (LF))
Odontocete	Ziphiidae	Arnoux's bekaed whale (*Berardius arnuxii* (HF))
Odontocete	Ziphiidae	Southern bottlenose whale (*Hyperoodon planifrons* (HF))
Odontocete	Ziphiidae	Gray's beaked whale (*Mesoplodon grayi (*HF))
Odontocete	Ziphiidae	Strap-toothed whale (*Mesoplodon layardii* (HF))
Odontocete	Ziphiidae	Cuvier's beaked whale (*Ziphius cavirostris* (HF))
Odontocete	Delphinidae	Long-finned pilot whale (*Globicephala melas* (HF))
Odontocete	Delphinidae	Hourglass dolphin (*Lagenorhynchus cruciger* (VHF))
Odontocete	Delphinidae	Killer whale (*Orcinus orca* (HF))
Odontocete	Phocoenidae	Spectacled porpoise (*Phocoena dioptrica* (VHF))
Odontocete	Physeteridae	Sperm whale (*Physeter macrocephalus* (HF))
Pinniped	Phocidae	Southern elephant seal (*Mirounga leonina* (PCW))
Pinniped	Phocidae	Leopard seal (*Hydrurga leptonyx* (PCW))
Pinniped	Phocidae	Weddell seal (*Leptonychotes weddellii* (PCW))
Pinniped	Phocidae	Crabeater seal (*Lobodon carcinophaga* (PCW))
Pinniped	Phocidae	Ross seal (*Ommatophoca rossii* (PCW))
Pinniped	Otariidae	Antarctic fur seal (*Arctocephalus gazella* (OCW))

Noise impacts to the hearing of marine mammals are a critical concern for regulatory agencies with injury to the auditory system generally considered a threshold above which more serious harm can occur. Although countries with environmental management frameworks for regulating ocean noise seek to mitigate injurious impacts to marine mammal hearing, a lack of consensus on the legal or regulatory definition of "injury" between countries contributes to differences in the noise thresholds at which impacts are regulated. For example, referencing Article 44(1) of Germany's Federal Nature Conservation Act (BNatSchG), injury has been interpreted as any form of hearing impairment: "An injury within the meaning of the prohibition on taking under species protection law is an impairment of an animal's physical welfare or damage to its health. This encompasses any impairment of its physical integrity (Bundesministerium Für Umwelt, 2014)." Thus, a temporary noise-induced hearing loss (NIHL), otherwise termed a temporary threshold shift (TTS), has been considered injury under German law once the threshold for TTS has been exceeded, regardless of the magnitude of the shift (e.g. a 6 dB and a 60 dB shift are both considered injurious). Conversely, following the 1994 amendments to the Marine Mammal Protection Act (MMPA) of the United States (US), the National Marine Fisheries Service (NMFS), which holds authority to regulate activities that potentially impact marine mammals in territorial waters, adopted a definition of injury that involved the destruction of tissue (e.g. National Marine Fisheries Service, 2002; National Marine Fisheries Service, 2008). The definition was originally the basis for the legal distinction under the MMPA between permanent threshold shift (PTS), or permanent loss of hearing that was believed to arise from tissue damage (e.g. disarticulation of the middle ear bones, loss of inner hair cells), and TTS, which was believed to be a fully recoverable form of auditory fatigue. More recently, the legal threshold for impacts that are considered injurious has been recommended as a 40 dB TTS (see section D.9), but without agreement that empirical evidence of injury associated with an initial TTS of 40 dB exists (Southall et al., 2019).

Regulated marine mammal sound exposure criteria and thresholds also vary between nations (e.g. Stöber and Thomsen, 2019). Germany, which is primarily concerned with the harbor porpoise (*Phocoena phocoena*) in the North Sea, regulates the risk of auditory injury by prescribing an unweighted 160 dB sound exposure level (SEL; dB re 1 $\mu Pa^2 s$) and an unweighted 190 dB instantaneous peak sound pressure level ($L_{p,\mathrm{pk}}$; dB re 1 µPa) as thresholds that cannot be exceeded within 750 m of the source for single noise events, such as a pile strike (see Bundesministerium Für Umwelt, 2014). The threshold is simple and easily applied and is based on work conducted by Lucke et al. (2009) measuring TTS in a harbor porpoise exposed to a seismic airgun. Similar approaches are used by other countries to regulate the seismic industry (e.g. Australian Government, 2008), although they may apply different distance limits or threshold values (e.g. Rumes and Debosschere, 2018). The US employs a more complicated system to accommodate the wide variety of marine mammal species. Marine mammal species are assigned to species groups and thresholds for impact are specified using either weighted or unweighted exposures; all non-impulsive signals utilize weighted SEL criterion, and impulsive signals use a dual criterion of weighted SEL and unweighted $L_{p,\mathrm{pk}}$ (NMFS 2018, Houser et al. 2017, Southall et al. 2019). The weighted SEL is determined by accumulating the energy received at the marine mammal over the period of some event. The unweighted $L_{p,\mathrm{pk}}$ is determined per noise impulse. TTS is assumed to occur once a 6 dB shift in the hearing threshold occurs. The onset of injury is estimated by extrapolating to 40 dB of TTS using a TTS growth function (i.e. change in threshold shift as a function of the change in received level, both in dB). Other countries have either implemented or recommended using similar procedures, albeit with modifications to numeric thresholds or procedures based upon the scientific studies emphasized (e.g. Tougaard et al., 2015; Andersson et al., 2016).

Regulating marine mammal noise exposure in Antarctic waters presents a challenge. Thresholds at which anthropogenic sound exposure cause either TTS or PTS in any Antarctic species is unknown; no Antarctic marine mammal has been directly involved in TTS research and no PTS research has intentionally been conducted on any marine mammal. From a regulatory perspective then, consideration of exposure thresholds in Antarctic species that result in TTS, whether or not it is considered injurious, are wholly dependent upon related species in which such studies have been conducted. Until such time that relevant research on hearing and NIHL is performed in Antarctic marine mammals, the estimates at which auditory system impacts occur will be best served through association with closely related surrogate species.

D.2 Association with surrogate species

The species for which TTS investigations have been conducted are listed in Table D. 2. Since few species have been used in TTS research, these species have necessarily served as representatives for other species for which no empirical measures of TTS exist. There are no more than four species representatives for any of the hearing groups proposed by Southall et al. (2019): two species represent the high-frequency (HF) odontocetes, two species represent the very high-frequency (VHF) odontocetes, four species represent the phocid carnivores in water and air (PCW and PCA), and one species represents the otariid carnivores (and other carnivores) in water and air (OCW and OCA). No direct measurements of hearing or investigations of TTS have ever been performed in mysticete whales, which comprise the low-frequency (LF) group. Estimates of mysticete hearing ranges have thus been informed from vocalization frequency ranges, anatomical modeling (Houser et al., 2001; Parks et al., 2007; Tubelli et al., 2012; Cranford and Krysl, 2015), and observations of responses to anthropogenic noise (e.g. Watkins, 1981; Richardson et al., 1986; Greene, 1987; Richardson et al., 1990; Frankel et al., 1995; Richardson et al., 1999; Frankel and Clark, 2000; Frankel and Clark, 2002; Castellote et al., 2012; Robertson et al., 2013). Predictions of TTS onset in mysticetes have further required extrapolation from TTS data collected with non-mysticete marine mammals (Southall et al., 2007; Finneran, 2016; Southall et al., 2019).

Table D. 2: Marine mammal species involved in TTS studies and the types of sounds used as fatiguing stimuli. The letters after each species name corresponds to the hearing group classification of Southall et al. (2019): LF – low frequency, HF – high frequency, VHF – very high frequency, PCW – phocid carnivores in water, OCW – other carnivores in water.

Species	Reference	Fatiguing noise types
Bottlenose dolphin (*Tursiops truncatus* (HF))	(Finneran et al., 2000; Schlundt et al., 2000; Finneran et al., 2002; Nachtigall et al., 2003; Nachtigall et al., 2004; Finneran et al., 2005; Finneran et al., 2007; Mooney et al., 2009b; Mooney et al., 2009a; Finneran et al., 2010a, b; Finneran and Schlundt, 2010; Finneran and Schlundt, 2013; Finneran et al., 2015)	Single impulse, multiple impulses Tone Continuous broadband noise, octave-band noise Simulated sonar
Beluga (*Delphinapterus leucas* (HF))	(Finneran et al., 2000; Schlundt et al., 2000; Finneran et al., 2002; Popov et al., 2011; Popov et al., 2013; Popov et al., 2014; Popo	Single impulse Tone ½-octave band noise

Species	Reference	Fatiguing noise types
Harbor porpoise (*Phocoena phocoena* (VHF))	(Lucke et al., 2009; Kastelein et al., 2012a; Kastelein et al., 2013b; Kastelein et al., 2014b; Kastelein et al., 2014a; Kastelein et al., 2015b; Kastelein et al., 2015a; Kastelein et al., 2016; Kastelein et al., 2017a; Kastelein et al., 2017b; Kastelein et al., 2020b; Kastelein et al., 2020c; Kastelein et al., 2020e)	Single impulse, multiple impulses Tone, narrowband noise Octave band noise FM sweeps
Finless porpoise (*Neophocaena phocaenoides* (VHF))	(Popov et al., 2011)	½-octave band noise
Harbor seal (*Phoca vitulina* (PCW))	(Kastak et al., 1999; Kastak et al., 2005a; Kastelein et al., 2012b; Kastelein et al., 2013a; Kastelein et al., 2018; Kastelein et al., 2019b; Kastelein et al., 2019a; Reichmuth et al., 2019; Kastelein et al., 2020a; Kastelein et al., 2020d)	Broadband noise, octave band noise Tone, narrowband noise
California sea lion (*Zalophus californianus* (OCW))	(Kastak et al., 1999; Finneran et al., 2003; Kastak et al., 2005a)	Single impulse Octave band noise
Northern elephant seal (*Mirounga angustirostris* (PCW))	(Kastak et al., 1999; Kastak et al., 2005a)	Octave band noise
Spotted seal (*Phoca largha* (PCW))	(Reichmuth et al., 2016)	Single impulse
Ringed seal (*Pusa hispida* (PCW))	(Reichmuth et al., 2016)	Single impulse

The species that are the best surrogates for predicting TTS in Antarctic species are those for which the auditory system anatomy and sound production and hearing characteristics are known to be similar, for which there is a close phylogenetic relationship, and for which TTS data exist. These are the same characteristics used to develop the proposed hearing groups of Southall et al. (2019). Based on these requirements, the best potential surrogates for some of the Antarctic delphinids are the bottlenose dolphin (*Tursiops truncatus*) and beluga (*Delphinapterus leucas*). These species are phylogenetically related to the long-finned pilot whale (*Globicephala melas*) and killer whale (*Orcinus orca*), have hearing ranges and echolocation signals that are similar in bandwidth (Pacini et al., 2010; Branstetter et al., 2017), and have similar auditory system anatomy (Ketten, 1997; Ketten, 2000). Likewise, the only Antarctic porpoise (*Phocoena dioptrica*) is logically best represented by the two porpoise species for which TTS data exist, specifically the harbor porpoise and the finless porpoise (*Neophocaena phocaenoides*). All of these species produce narrow-band, high-frequency echolocation signals, which differentiates them from delphinids or monodontids that produce broadband, impulsive echolocation signals. Although a delphinid, the hourglass dolphin (*Lagenorhynchus cruciger*) could similarly utilize porpoises as surrogates as it also produces narrowband high-frequency clicks that suggest it might also be a high-frequency hearing specialist (Kyhn et al., 2009; Tougaard and Kyhn, 2010).

Phocid seals are the most represented of the marine mammal groups within the TTS literature, which provides strong collective justification for group surrogacy of untested Antarctic phocids. However, even though there are similarities in the auditory system anatomy of different phocid species and evidence suggests that all phocids have a higher upper frequency limit of hearing underwater than in air, data on TTS and underwater hearing is dominated by the phocinid seals (Table D. 3, Mohl, 1968; Terhune and Ronald, 1972; Terhune and Ronald, 1975; Terhune, 1988; Babushina, 1997; Kastelein et al., 2009a; Kastelein et al., 2009b; Reichmuth et al., 2013; Sills et al., 2014; Sills et al., 2015). All Antarctic phocids are monachid seals. Although limited hearing information exists for the Hawaiian monk seal (*Monachus schauinslandi*, Thomas et al., 1990; Ruscher-Hill et al., 2019), hearing and TTS data both exist in only one monachid, the northern elephant seal (*Mirounga angustirostris*, Kastak and Schusterman, 1999; Kastak et al., 1999; Kastak et al., 2005a). Extrapolation of the collective phocid TTS data to Antarctic seals should therefore consider the unbalanced representation toward phocinids, albeit the uncertainty in the extrapolation is probably much less than if extrapolating from species outside the Phocidae.

Table D. 3: List of marine mammal TTS studies conducted with impulsive sources and arranged by the number of impulses to which the animal subjects were exposed. Exposure levels are unweighted. ($L_{p,pk}$-pk – peak-to-peak sound pressure level; $L_{p,pk}$ – peak sound pressure level; SEL – sound exposure level, single event; SEL_{cum} – cumulative sound exposure level across multiple exposures; * hearing threshold obtained by AEP methods).

Exposure type	Species	Source	Max TTS	Max exposure	Reference
Single impulse	T. truncatus, D. leucas	Explosion simulator	No TTS observed	221 dB $L_{p,pk-pk}$ 179 dB SEL	(Finneran et al., 2000)
Single impulse	T. truncatus, D. leucas	Seismic water gun	7 dB at 400 Hz	226 dB $L_{p,pk-pk}$ 186 dB SEL	(Finneran et al., 2002)
Single impulse	Z. californianus	Arc-gap transducer	No TTS observed	205 dB $L_{p,pk-pk}$ 163 dB SEL	(Finneran et al., 2003)
Single impulse	P. phocoena	Air gun	15 dB at 4 kHz*	202 dB $L_{p,pk-pk}$ 166 dB SEL	(Lucke et al., 2009)
Single impulse	P. largha	Air gun	No TTS observed	207 dB $L_{p,pk-pk}$ 181 dB SEL	(Reichmuth et al., 2016)
Single impulse	P. hispida	Air gun	No TTS observed	207 dB $L_{p,pk-pk}$ 181 dB SEL	(Reichmuth et al., 2016)
10 impulses	T. truncatus	Air gun	9 dB at 8 kHz*	212 dB $L_{p,pk-pk}$ 195 dB SEL_{cum}	(Finneran et al., 2015)
Up to 20 impulses	P. phocoena	Multiple air guns	4 dB at 4 kHz	199 dB $L_{p,pk}$ 191 dB SEL_{cum}	(Kastelein et al., 2017b)
2760 impulses	P. phocoena	Playback of pile driving sounds	2 dB at 4 kHz; 4 dB at 8 kHz	180 dB $L_{p,pk}$ (max possible) 180 dB SEL_{cum}	(Kastelein et al., 2015b)

Exposure type	Species	Source	Max TTS	Max exposure	Reference
Up to 16,560 impulses	P. phocoena	Playback of pile driving sounds	~5 dB at 8 kHz	?? dB $L_{p,pk}$ 187 dB SEL_{cum}	(Kastelein et al., 2016)
Up to 16,560 impulses	P. vitulina	Playback of pile driving sounds	~4 dB at 4 kHz	?? dB $L_{p,pk}$ 193 dB SEL_{cum}	(Kastelein et al., 2018)
Up to 40 impulses	P. phocoena	Single and multiple airguns	~4 dB at 4 kHz	202 dB $L_{p,pk}$ 191 dB SEL_{cum}	(Kastelein et al., 2020e)

There is only one Antarctic otariid, the Antarctic fur seal (*Arctocephalus gazella*), and only one otariid for which hearing and TTS data both exist, the California sea lion (*Zalophus californianus*). Audiometric information suggests that California sea lions and northern fur seals (*Callorhinus ursinus*) have similar upper frequency limits of hearing underwater, which is less than the upper frequency limit of the phocids underwater, and share similar absolute sensitivities to underwater sound (Schusterman et al., 1972; Moore and Schusterman, 1987; Babushina et al., 1991; Mulsow et al., 2012; Reichmuth and Southall, 2012; Reichmuth et al., 2013). Partial underwater audiograms also exist for the Steller sea lion (*Eumatopius jubatus*) but the upper frequency limits of hearing are not well-defined (Kastelein et al., 2005). However, electrophysiological audiograms suggest that both the upper limit of hearing and sensitivity to sound in air is consistent between California and Steller sea lions (Mulsow and Reichmuth, 2010; Mulsow et al., 2011a; Mulsow et al., 2011b; Mulsow et al., 2014). Since the available evidence suggests that hearing ranges and sensitivities are consistent across otariid species, and since TTS data only exist for the California sea lion, the California sea lion seems the most reasonable surrogate for the Antarctic fur seal.

The remaining groups of Antarctic marine mammals – the beaked whales, sperm whale, and mysticete whales – have no closely related species for which TTS data exist. Sperm and beaked whales share a *physeteroid* ear, which distinguishes them from other odontocetes (Nummela, 2008). However, echolocation frequencies of beaked and sperm whales (e.g. Backus and Schevill, 1966; Mohl et al., 2003; Wahlberg et al., 2011; Baumann-Pickering et al., 2013; Stimpert et al., 2014), and electrophysiological hearing measurements in a neonate sperm whale and two species of beaked whale (Ridgway and Carder, 2001; Cook et al., 2006; Finneran et al., 2009; Pacini et al., 2011), suggest that these whales likely have hearing sensitivity at frequencies to which other HF odontocetes are adapted. Although beaked whales generally produce frequency-modulated sweeps for echolocation as opposed to broadband clicks typical of most other delphinid odontocetes (e.g. Baumann-Pickering et al., 2013), the frequency range covered is generally much lower than the narrowband high-frequency (>100 kHz) signals produced by porpoises and some delphinids (the VHF odontocetes). For this reason, the most closely associated group of odontocetes from which TTS predictions can be extrapolated are likely the bottlenose dolphin and beluga.

Predicting levels of sound required for the onset of TTS in Antarctic mysticetes is particularly difficult. Not only has no TTS study ever been conducted in a mysticete whale, no hearing test has been performed either. The anatomical adaptations of the middle and inner ear are consistent with low-frequency specialization and are distinct from that of the odontocetes (Ketten, 1992, 2000; Nummela, 2008). Nevertheless, without direct measurements of TTS from which to work, NMFS (2018) and Southall et al. (2019) formulated weighting functions and onset TTS threshold predictions for mysticetes by extrapolating data from odontocetes and integrating it with anatomically-based predictions of the audiogram. The approach potentially produces substantial errors in onset TTS predictions, but it presumably contains less error than if extrapolations were based solely on terrestrial mammal data (of which there is also little for low-frequency specialists). A summary of proposed surrogates and rationale for surrogacy are provided in Table D. 4.

Table D. 4: List of possible surrogates for Antarctic species based upon species for which TTS data are available. Potential rationale for the surrogacy are based upon phylogenetic relationships, ear type, hearing range, and similarities in sound production.

Antarctic Species	TTS Surrogate(s)	Rationale
long-finned pilot whale, killer whale	bottlenose dolphin, beluga	phylogeny (bottlenose dolphin), ear type and hearing range similarity, sound production similarity
Antarctic porpoise	harbor porpoise, finless porpoise	phylogeny, ear type similarity, sound production similarity
hourglass dolphin	harbor porpoise, finless porpoise	ear type and sound production similarity
southern elephant seal, leopard seal, Weddell seal, crabeater seal, Ross seal	harbor seal, spotted seal, ringed seal, northern elephant seal	phylogeny, ear type similarity[19]
Antarctic fur seal	California sea lion	phylogeny, ear type similarity
Arnoux's bekaed whale, southern bottlenose whale, Gray's beaked whale, strap-toothed whale, Cuvier's beaked whale	bottlenose dolphin, beluga	phylogeny (toothed whale)[20]
sperm whale	bottlenose dolphin, beluga	phylogeny (toothed whale)[21]

D.3 Types of noise and assignments to Antarctic noise sources

The types of noise used to study TTS in marine mammals are broadly aligned both with the types of anthropogenic noise encountered in the ocean and with the types of noise traditionally used to study TTS in terrestrial laboratory animals. The characteristics of the noise, including such things as bandwidth, peak pressure, and energy all contribute to the frequencies of hearing affected and the magnitude of the threshold shift (see below). Fatiguing noise types can be categorized as steady-state (non-impulsive) or impulsive, and both can be considered as intermittent depending on the duty cycle of the source.

Steady-state noise sources used to study TTS in marine mammals have included both broadband and narrowband/tonal sounds. Broadband steady-state noise used in TTS studies has generally been either octave band or half-octave band white noise. The duration of exposure to these

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[19] All Antarctic seals are monachids. Most TTS work done with phocinid seals.

[20] No direct phylogenetic grouping.

[21] No direct phylogenetic grouping.

sources has ranged from as little as 1 min to as long as 4 hrs (e.g. Kastak et al., 2005a; Mooney et al., 2009b; Popov et al., 2011; Kastelein et al., 2012a). Conversely, experimental subject exposure to narrowband noise (1/6-octave band) and tonal signals, including narrowband frequency sweeps, have typically been no more than one hour in duration (e.g. Kastelein et al., 2019b; Kastelein et al., 2020a; Kastelein et al., 2020d) and as short as one second (e.g. Schlundt et al., 2000).

Impulsive signals are short duration, producing very fast changes in pressure and high peak pressures that result in acoustic energy spread across a broad frequency bandwidth. Impulsive signals are generally considered to be more hazardous to hearing than other types of sound (Henderson and Hamernik, 1986). Examples include gun shots, explosions, pile driving strikes, and seismic airgun shots. It should be noted that regulatory agencies and advisory groups from different countries do not necessarily agree on what constitutes an impulsive sound source. For example, US regulators do not classify sonar signals as impulsive (National Marine Fisheries Service, 2018), whereas recommendations to the EU Marine Strategy Framework Directive suggest that sonar signals should be included in the analysis of “short duration” signals, which includes impulses (Dekeling et al., 2014). Regardless of regulatory classification, impulsive sources used in the study of TTS have involved an explosion simulator (Finneran et al., 2000), seismic water gun (Finneran et al., 2002), arc-gap transducer (Finneran et al., 2003), seismic airgun(s) (Lucke et al., 2009; Finneran et al., 2015; Reichmuth et al., 2016; Kastelein et al., 2017b), and playbacks of various impulsive sounds (Kastelein et al., 2015b; Kastelein et al., 2016; Kastelein et al., 2018).

Intermittency is common to many, but not all noise sources, and can be characteristic of both steady-state and impulsive noise. From the perspective of a marine mammal, ship noise would generally be continuous throughout the period it is audible whereas explosions might be single events. However, sources such as sonars, seismic airguns, and underwater pile driving typically have repetitive sound emission with durations of quiet between emissions dependent upon operational needs or hardware limitations. Intermittency is important when considering how the ear is fatigued by noise, as the ear generally recovers between periods of sound exposure (see section D.6).

D.3.1 Antarctic noise sources

Many of the noise sources used in studies of NIHL are not truly representative of noise sources in the Southern Ocean. Real-world noise sources vary in amplitude and spectral characteristics due to duty cycle and/or movement of the platform, acoustic interactions with the environment, and further variation in the received noise dependent upon the three-dimensional movement of an exposed marine mammal. Nevertheless, each noise source’s characteristics can be coarsely aligned to one or more of the noise types used in the study of marine mammal TTS.

Vessels

Research vessels, commercial tourist vessels, authorized and unauthorized fishing vessels, and privately owned vessels all utilize the waters of the Antarctic (Antarctic Southern Ocean Coalition, 2008). While underway, ships have a continuous noise signature due to fuel drive systems, propeller cavitation, and other noise sources onboard the ship that transmit through the hull. Noise levels vary with the speed of travel and peak at certain speeds due to propeller cavitation. Ship noise is generally broadband and can range from 10 Hz to ~100 kHz (Veirs et al., 2016). Noise radiation is not truly omnidirectional, but rather generally conforms to a dipole transmission at the lowest frequencies with shadowing and noise scattering due to interactions between the noise field and the ship's hull (Arveson and Vendittis, 2000). Source levels can be high, reaching a sound pressure level (L_p; rms pressure in dB re 1 µPa) of nearly 197 dB L_p for ice breakers underway and up to 205 dB L_p during active ice breaking (Erbe and Farmer, 2000). For purposes of auditory impacts, vessels would generally be considered a continuous noise source (however, see Martin et al., 2020 for the possible relationship between ship noise kurtosis and the impulsive nature of ship noise).

Marine seismic airguns

Marine seismic airguns produce intermittent, impulsive sounds used to generate downward projected, low-frequency signals for geophysical exploration. Airguns are typically towed behind ships in arrays; the configuration of the array, the number of airguns employed, the tow depth, and the volume of compressed air used (and degree of compression) can be configured to achieve specific exploration goals. Airgun arrays are shallowly towed and the initial signal from an airgun is reflected off of the ocean surface to achieve the desired downward propagation of low-frequency sound (Caldwell and Dragoset, 2000). Thus, the airgun signal consists of an initial high-pressure impulse quickly followed by an inverted form of the initial wave due to surface reflection. Depending on the design of the array, source levels can exceed peak-peak sound pressure levels ($L_{p,\mathrm{pk\text{-}pk}}$; dB re 1 µPa) of 220 dB (e.g. Hermannsen et al., 2015). The majority of the acoustic energy contained within an airgun signal is generally < 1000 Hz (Caldwell and Dragoset, 2000; Tashmukhambetov et al., 2008; Lucke et al., 2009); although undesirable, higher frequency components are also observed. The duty cycle of an airgun array varies depending on exploration needs, although repetition rates of once every 10-20 s are common. For purposes of assessing auditory impacts to marine mammals, seismic airguns would be considered intermittent, impulses. However, reassignment of this classification might be required for receivers far from the noise source where the impulse nature of the signal becomes degraded (see section D.8).

Bathymetric profilers

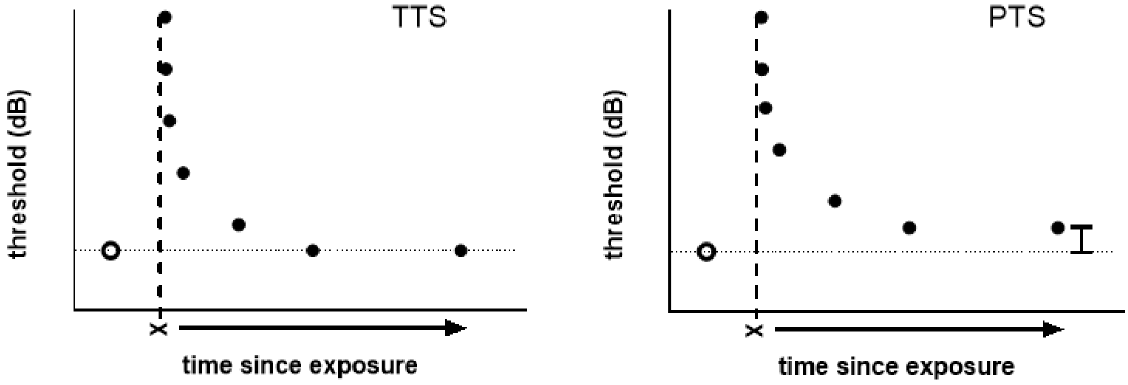
Bathymetric profilers (bottom and sub-bottom) are echosounders used to map the ocean floor and/or its sub-surface. They may be either single beam or multi-beam projecting either downward along the ship track or transverse to it. Bathymetric profilers are varied in their configuration and operational characteristics - they can span frequencies of a few kHz to tens of kHz and significantly vary the pulse duration and duty cycle according to the depth of the bathymetry. Source levels are typically high; for example, maximum source levels of 239 dB L_p and 245 dB L_p have been reported for the Hydrosweep and Parasound, respectively (*see associated report on sound sources*). Pulse durations are typically short (<100 ms), which lessens the total energy of individual pings, and pulse repetition rates are dictated by the depth of the bathymetry investigated (e.g. common repetition rates vary from 0.1 Hz (1 pulse/10 s) to ~2 Hz (2 pulse/s) depending upon the depth of the ocean floor). Signals from bathymetric profilers are intermittent, although the relevancy of how the intermittency affects marine mammals depends largely on the time between pings. Whether or not the signal is impulsive will depend largely on the characteristics applied to the individual ping (e.g. although not standard configuration, the Parasound can produce signals with pulse durations of ~170 µs).

D.4 NIHL test methods and impact to interpretation

D.4.1 NIHL testing overview

Experiments characterizing NIHL generally follow the same pattern: 1) one or more hearing measurements are made before exposure of the subject animal to a fatiguing noise; 2) the animal is exposed to the fatiguing noise; 3) one or more measurements are conducted over a time period following the noise exposure. An NIHL is determined when a change in an animal's hearing threshold following the fatiguing noise exposure is measured. The hearing threshold is the lowest level of sound that can be detected by the animal in a quiet environment and the threshold increases when there is an NIHL. If the loss of hearing completely recovers over time, i.e. the threshold of hearing returns to normal, the NIHL is a TTS (Figure D. 1). If, however, hearing sensitivity never fully recovers, then the remaining NIHL is a PTS. The severity of the shift is determined by subtracting the shifted threshold from the baseline threshold (in dB). For noise exposure experiments involving marine mammals, thresholds have been determined either behaviourally or by measuring small voltages from the brain produced in response to hearing a sound, the so-called auditory evoked potential (AEP).

Figure D. 1: (Left) The threshold of an animal is measured before an exposure (open circle). Upon receiving a noise exposure (X and vertical dashed line), an increase in the threshold occurs. If the threshold returns to the pre-exposure threshold over time (horizontal dotted line), it is a TTS. (Right) If the threshold does not return to the pre-exposure threshold over time, the remaining NIHL is a PTS. At any point in time, the difference between the shifted threshold and the baseline threshold is the magnitude of the threshold shift (demonstrated by the vertical bar).



Source: Author's own.

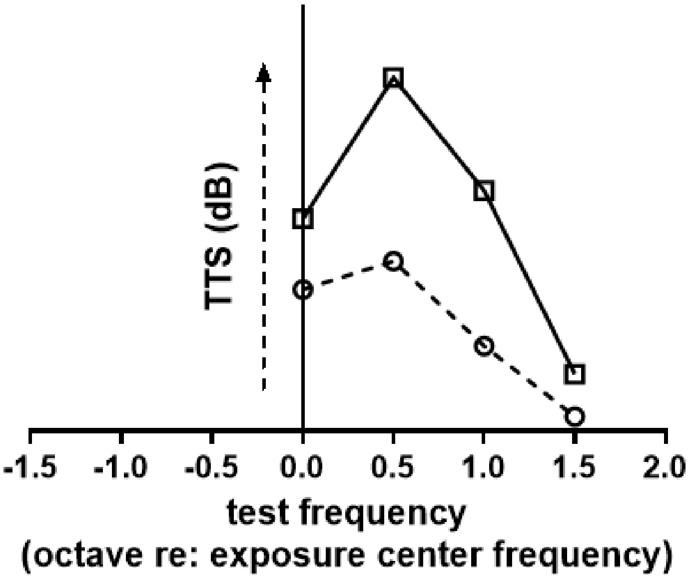
D.4.2 Behavioral and auditory evoked potential (AEP) test methods

Behavioral measurements of hearing, which require an animal to make an action in response to hearing a sound (e.g. paddle push, produce a whistle), provide an integrated animal response that includes the animal's perception of the sound and its decision to respond. The use of AEP methods is generally more rapid than behavioral methods and allows testing of multiple frequencies simultaneously; however, it measures only voltages generated by certain portions of the ascending auditory system (i.e. it is not an integrated animal response). Temporary threshold shifts determined with AEP methods generally demonstrate an earlier onset of TTS and shifts of greater magnitude than that observed with behavioral methods, suggesting that some form of accommodation enables behavioral thresholds to be restored even when the auditory system has not fully recovered (Finneran et al., 2007; Finneran et al., 2015). Finneran et al. (2007) showed that TTS measured with AEPs were 19-33 dB greater than those measured behaviorally and that threshold shifts of ~10 dB were found in the absence of any behavioral shift. In addition, recovery measured with AEPs were always longer than those measured behaviorally. In a later study involving air gun exposures, no changes in behavioral thresholds were observed whereas a small amount of TTS was observed using AEP methods (Finneran et al., 2015); in one of the dolphins, a 9 dB TTS was observed at 8 kHz. Thus, when considering the outcomes of TTS studies, caution should be exercised in making comparisons between studies that used different threshold measurement methods and any synthesis of findings across studies should also take these differences into account (see section D.9).

D.4.3 Frequency of noise exposure vs. frequency of testing

Careful selection of hearing test frequencies must be made in relation to the frequencies of the fatiguing noise exposure. As in terrestrial mammals, it has been demonstrated in marine mammals that TTS can occur at frequencies ranging from the center frequency to one octave above the center frequency of the noise exposure (Nachtigall et al., 2004; Kastak et al., 2005a; Finneran et al., 2007; Mooney et al., 2009b; Popov et al., 2011; Kastelein et al., 2012b; Kastelein et al., 2012a; Kastelein et al., 2013b; Popov et al., 2013; Kastelein et al., 2019b; Kastelein et al., 2020a; Kastelein et al., 2020d). Where the greatest TTS occurs likely depends on many factors, such as the species tested, the bandwidth of the noise, and the temporal and spectral characteristics of the noise. The L_p is also critical; as the L_p of the noise exposure increases there is an upward spread in the frequencies most affected by TTS (Figure D. 2, and also see Mcfadden, 1983), which is due to a spread in the excitation patterns along the cochlear partition as cochlear filters broaden in direct relation to the L_p. Evidence for this phenomenon has been found in the harbor porpoise and harbor seal (Kastelein et al., 2014a; Kastelein et al., 2019b; Kastelein et al., 2019a; Kastelein et al., 2020a; Kastelein et al., 2020d), both of which showed a transition from the greatest TTS occurring at the frequency of the fatiguing exposure to ⅓- or ½-octave above the frequency of the fatiguing exposure as the L_p of the stimulus increased. The pattern might, however, be somewhat dependent upon the fatiguing noise frequency; for example, tests in the harbor seal showed the highest frequency of fatiguing noise (1/6-octave centered at 40 kHz) consistently yielded higher levels of threshold shift ~1/3-octave above the noise center frequency independent of the exposure level (Kastelein et al., 2020d).

Figure D. 2: TTS can be greater up to an octave above the center frequency of the noise exposure. Depending on the frequency tested, the magnitude of the TTS can spread upward in frequency as the noise Lp increases. (open circles = lower Lp; open squares = higher Lp).



Source: Author’s own.

D.5 Temporary threshold shift

D.5.1 Overview of species studied

A considerable body of literature has been established on acoustic factors that produce TTS in marine mammals. Because TTS studies have primarily been conducted with marine mammals under human care, there are a limited number of subjects and species that have been tested. The marine mammal species that have been used to study TTS are listed in Table D. 2, along with a listing of the research references and the types of fatiguing noises used to induce TTS. A more comprehensive table with more detailed study information is provided in D.13.

The largest number of TTS studies have been conducted with odontocete cetaceans. Within the odontocetes, the bottlenose dolphin and beluga are the sole representative species of the Delphinidae and Monodontidae families. The Phocoenidae are represented by the harbor porpoise and the finless porpoise; however, the representation in TTS studies is greatly skewed toward the harbor porpoise as the finless porpoise has been the subject of only one study. Odontocete studies have involved all of the sound types previously described: steady-state broadband, narrowband, and tonal stimuli, and both single and multiple impulses from multiple sound sources.

The representation of pinnipeds in TTS studies is largely by the Phocidae. The harbor seal, spotted seal (*Phoca largha*), and ringed seal (*Pusa hispida*) represent the phocinid seals while the northern elephant seal is the sole representative of the monachid seals. As with the harbor porpoise, the majority of TTS studies involving phocid seals has involved the harbor seal, which has been subject to TTS studies involving steady-state broadband and narrowband noise, as well as impulsive noise. The ringed and spotted seals have only been tested with impulses as the fatiguing stimulus, whereas the northern elephant seal has only been tested with octave band noise as the fatiguing stimulus. The only representative of the otariid seals, the California sea lion, has been tested with single impulses and octave band noise as fatiguing stimuli.

D.5.2 L_p, Duration, and Frequency

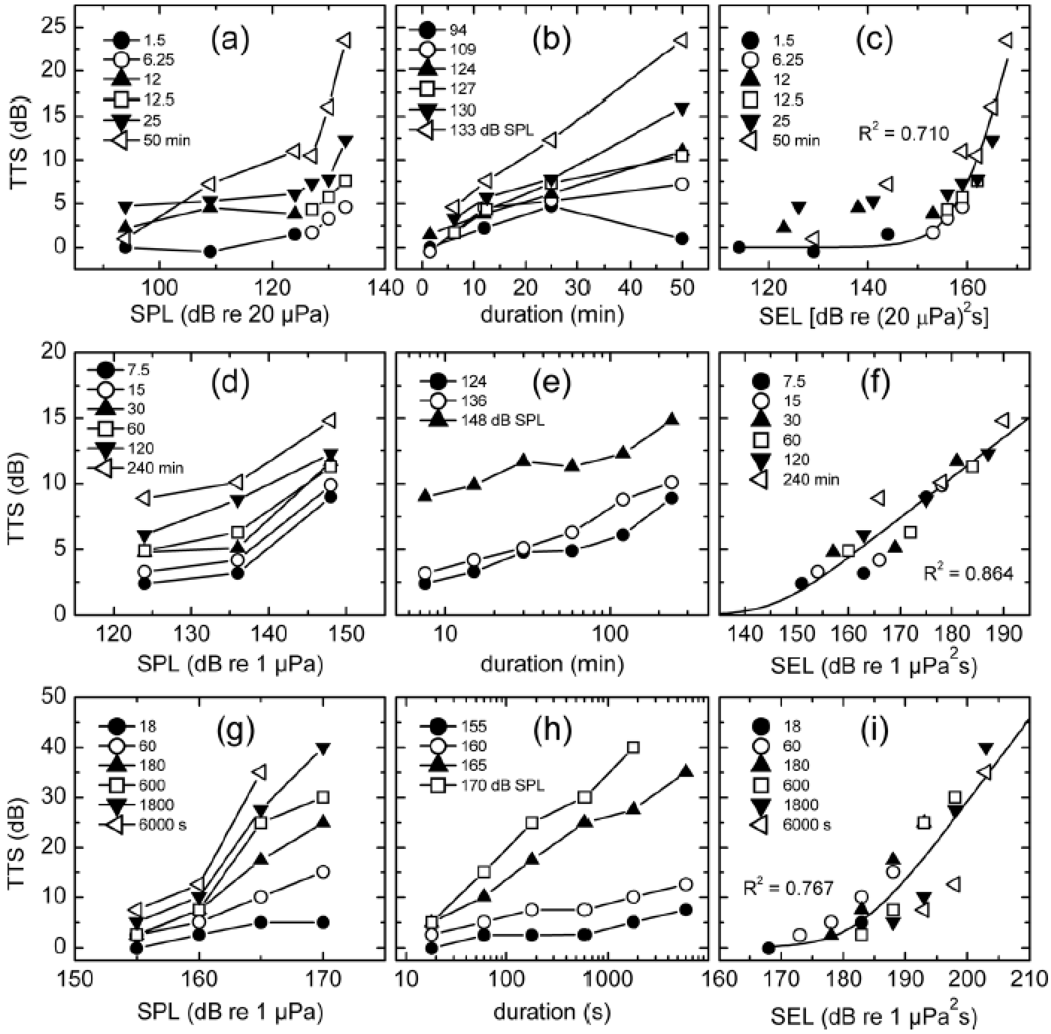
Steady-state signals

In general, if a fatiguing noise is held at a fixed duration, TTS grows in a direct but non-linear relationship to the L_p of the fatiguing noise (Figure D. 3 a,d,g). This pattern has been observed in terrestrial mammals and marine mammals (e.g. Kastak et al., 2007; Kastelein et al., 2012a; Popov et al., 2014). Temporary threshold shift also grows with the logarithm of signal duration when the L_p of the fatiguing noise is held constant (see Figure D. 3 b,e,h, Popov et al., 2014; Finneran, 2015). Since TTS is dependent on both the duration and L_p of a noise, the onset and growth of TTS is often described with respect to the noise SEL.

The growth of TTS in marine mammals exposed to steady-state signals as a function of the SEL increases in a curvilinear manner. However, the noise L_p and exposure duration interact in a complex fashion that is not easily predicted. Linear portions of TTS growth vs. SEL in marine mammals demonstrate growth rates from 0.2 to 4.5 dB TTS/dB SEL. The broad range in TTS growth rates is due to variation between species and the characteristics (such as bandwidth and duty cycle) of the noise causing the TTS (e.g. Finneran and Schlundt, 2013; Kastelein et al., 2014a; Finneran, 2015). The TTS growth rate has become an important factor in some regulations; specifically, TTS growth as a function of SEL has been proposed and implemented as a method by which injury (as defined in the US) might be predicted in marine mammals (National Marine Fisheries Service, 2018; Southall et al., 2019).

The onset and growth of TTS within a species varies with the frequency of the noise exposure. However, the amount of noise exposure necessary for TTS onset is not necessarily lower, nor the growth rate of TTS higher, at frequencies where animals have their best hearing. The growth rate of TTS to tonal exposures in bottlenose dolphins has been shown to be greatest at frequencies ranging from 14.1 to 28 kHz (Finneran and Schlundt, 2013), but the best hearing sensitivity of the bottlenose dolphin is between 40 and 80 kHz. Noise exposure levels required for TTS onset were highest at the lowest frequencies tested, but within 5 dB of one another at frequencies from 10-56 kHz. There is a tendency across TTS studies in bottlenose dolphins for requiring a higher SEL to cause TTS onset at frequencies <10 kHz (Finneran et al., 2005; Finneran et al., 2010a, b). Similar trends are not as clear in the harbor porpoise, but the methods employed are more variable across the harbor porpoise studies making interpretation more difficult (Lucke et al., 2009; Kastelein et al., 2012b; Kastelein et al., 2014b; Kastelein et al., 2014a; Kastelein et al., 2015a; Kastelein et al., 2017b). Differences in TTS growth rate and onset measured in belugas using electrophysiological methods also found that the growth of TTS was greater following exposures centered at 11.2 and 22.5 kHz than at higher frequencies (Popov et al., 2013). Similar electrophysiological measurements in the finless porpoise were not as conclusive (Popov et al., 2011). Nevertheless, the available information suggests that odontocetes (or at least delphinids) are possibly most susceptible to TTS in the frequency range of 10-40 kHz (Finneran, 2015).

Figure D. 3: TTS growth with exposure level and duration. The left, center, and right panels show the same data expressed as functions of sound pressure level (SPL), duration, and SEL, respectively. The values in the legends indicate the exposure duration for the left and right panels and the exposure SPL for the center panels. The units for the SPL and duration values in the legends match the abscissa units for the left and center panels, respectively. The solid lines in the right panels are nonlinear fits to the data. (a)–(c) Mean values of TTS in a California sea lion exposed to 2.5-kHz octave-band noise in air (Kastak et al., 2007). TTS was determined from behavioral hearing tests conducted 10 to 15 min post-exposure at a frequency of 2.5 kHz. (d)–(f) TTS in a harbor porpoise exposed to 4-kHz octave-band noise (Kastelein et al., 2012b). TTS was determined from behavioral hearing tests conducted 1 to 4 min post-exposure at a test frequency of 4 kHz. (g)–(i) TTS in a beluga exposed to 22.5-kHz half-octave band noise (Popov et al., 2014). TTS was determined from AEP measurements conducted 2-min post-exposure at a test frequency of 32 kHz.



Source: Reproduced from [Finneran, J.J., 2015. Noise-induced hearing loss in marine mammals: A review of temporary threshold shift studies from 1996 to 2015. J. Acoust. Soc. Am. 138(3), 1702-1726.], with the permission of the Acoustical Society of America.

With the exception of the harbor seal, little information on the relationship between the frequency of noise exposure and TTS onset and growth exists for pinnipeds. Kastelein et al. (2019b; 2020a; 2020d) investigated the onset and growth rate of TTS in the harbor seal at the center frequency of a 1/6-octave band noise exposure and at fractional-octave intervals up to one octave above the center frequency. The center frequencies of the narrowband noise tested were 16, 32 and 40 kHz. Similar to work in the dolphins, the TTS growth rates were found to vary depending on the frequency of the fatiguing noise and the frequency of hearing tested, with TTS growth rates typically being greater at hearing frequencies above the center frequency. A few other studies have been conducted in the California sea lion, elephant seal, and harbor seal, but these studies primarily used noise exposures with center frequencies limited to 2.5 and 4 kHz (Kastak et al., 2004; Kastak et al., 2005b; Kastak et al., 2007; Kastelein et al., 2012b; also, see Figs. 5(j)-(l) of Finneran, 2015), i.e. they covered only a limited frequency range.

Impulsive signals

The short duration, very fast changes in pressure, and high peak pressures that collectively contribute to acoustic energy spread across a broad frequency bandwidth are generally considered to make impulses more hazardous to hearing than other types of sound (Henderson and Hamernik, 1986). With respect to the potential for impulsive signals to cause TTS in marine mammals, multiple acoustic metrics have been proposed for characterizing the physical aspects of the impulsive signal that are associated with TTS. The most commonly used metrics are the SEL and the peak or peak-peak sound pressure level of the received signal.

Only a few marine mammal TTS experiments have been conducted in the laboratory with real-world impulsive sound sources because of the logistical difficulties of operating such sources and the difficulty of replicating signals as they would be received in the open ocean. The remainder of the studies have been performed with either playbacks of impulsive recordings or with a surrogate source (e.g. customized or non-industrial air gun); no studies have been conducted with explosive charges. A list of the marine mammal TTS studies conducted with impulsive sources is given in Table D. 3 (see also D.13). Generally, TTS resulting from exposure to impulsive signals has been difficult to achieve. In some instances, such as with ringed and spotted seals exposed to airgun shots (Reichmuth et al., 2016), TTS was not achieved at the highest unweighted exposure levels ($L_{p,\mathrm{pk\text{-}pk}}$=207 dB re 1 µPa; SEL=181 dB re 1 µPa^{2}s). Finneran et al. obtained similar results in two bottlenose dolphins and a beluga exposed to an impulse (max $L_{p,\mathrm{pk\text{-}pk}}$=221 dB re 1 µPa, max SEL=~179 dB re 1 µPa^{2}s) from an explosion simulator and two California sea lions exposed to impulses (max $_{p,\mathrm{pk}}$=203 dB re 1 µPa, max SEL=163 dB re 1 µPa^{2}s) from an arc-gap transducer (Finneran et al., 2000; Finneran et al., 2003). The largest TTS observed behaviorally was 7 dB in a beluga exposed to a seismic water gun (Finneran et al., 2002). The largest TTS measured with AEPs was 15 dB in a harbor porpoise exposed to a single seismic air gun impulse (Lucke et al., 2009). Consistent with TTS studies utilizing steady-state noise, the greatest shifts occurred between the center frequency of the exposure and one octave above. No shifts were noted at lower frequencies. Differences between AEP and behavioral measures of TTS were directly demonstrated by Finneran et al. (2015), who found no behavioral threshold shift after exposure to 10 impulses from an air gun (each impulse separated by 10 s; maximum cumulative, unweighted SEL from 193-195 dB re 1 µPa^{2}s), but did observe an AEP threshold shift of 9-dB in one dolphin tested at 8 kHz.

Because of the lack of data on TTS growth rates due to repetitive impulsive noise exposures, Southall et al. (2019) proposed using a growth rate of 2.3 dB TTS/dB SEL based on work conducted in chinchillas (Henderson and Hamernik, 1986). The approach was conservative in that it utilized the more extreme growth rates based on the highest noise exposures, but was deemed a necessary precautionary step given that data were being extrapolated from terrestrial mammals to marine mammals (Southall et al., 2007). As with steady-state signals, TTS growth as a function of impulse SEL has been proposed and implemented as a method by which injury (as defined in the US) might be predicted in marine mammals (National Marine Fisheries Service, 2018; Southall et al., 2019).

D.5.3 Relevance to Antarctic species

Predicting how noise exposure results in TTS and the growth of TTS in Antarctic species would necessarily rely on limited information with respect to both the surrogate species and frequencies tested. Southall et al. (2007; 2019) utilized various approaches to establishing TTS thresholds based upon species groupings, empirical data, and the use of auditory weighting to discount the inclusion of frequencies in a fatiguing noise to which animals were insensitive and enhance or preserve the response at frequencies where TTS susceptibility was high and hearing sensitivity was good (see section 0). Although there is no requirement for using the thresholds and species groupings proposed by Southall et al. (2019), it is recommended that any approach developed or adopted for use in Antarctic species employ a similar methodical process.

Southall et al. (2007; 2019) used a 1.6 dB TTS/dB SEL exchange rate to predict the growth of TTS as a function of increasing SEL for steady-state noise, and a 2.3 dB TTS/dB SEL for impulse noise. These were broadly applied to the species groups due to the limited number of species and frequencies for which TTS growth data exist (or for the lack of data in the case of impulse exposures). Data from representative species could be more specifically applied to Antarctic species, if desired; e.g. the TTS growth data behaviorally obtained from the bottlenose dolphin exposed to steady-state noise (Table D. 5) could be used to apply frequency-specific TTS growth rates to related Antarctic species (long-finned pilot whale, killer whale). In doing so, frequencies where higher growth rates occur could be predicted with greater specificity (e.g. the growth rate at 28 kHz (4.4 dB TTS/dB SEL) is substantially higher than growth rates <10 kHz or >40 kHz (both <0.5 dB TTS/dB SEL)). Unfortunately, behavioral data for TTS growth rates only exist across a broad range of frequencies for bottlenose dolphins (and possibly harbor seals), thus limiting the number of related species group extrapolations that could be performed. Additional species and frequencies could be included if AEP data were considered, but differences in AEP and behavioral data would need to be accounted for.

Table D. 5: Example of TTS growth rate data for the bottlenose dolphin exposed to CW signals of various duration and intermittency. Provided are the frequency at which the TTS was measured, the growth rate of TTS in dB of TTS/dB of SEL, and the number of dolphins tested to determine the growth rate. For the 3 kHz condition, one dolphin was tested multiple times and the average of the growth rates was used in the calculation of the grand average across individuals. (Data are from Finneran et al. 2005a, 2010a,b; Finneran and Schlundt, 2013.)

Frequency	TTS growth rate (dB/dB)	n
3	0.2	4
7.1	0.2	1
10	0.5	1
14.1	0.9	1
20	1.2	1
28.3	4.4	1
40	0.5	1

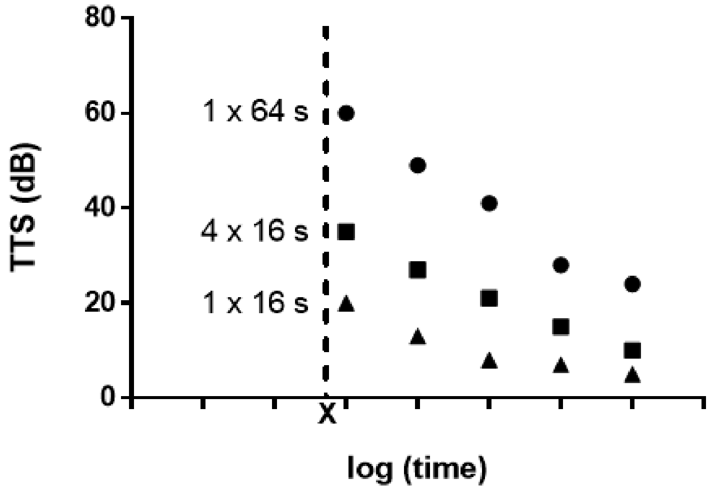
Frequency	TTS growth rate (dB/dB)	n
56.6	0.5	1

D.6 Exposure intermittence and hearing recovery

The ear recovers during quiet periods when it is not being exposed to noise. Two noise exposures with the same SEL but which differ in that one is continuous and one is intermittent will produce different levels of TTS (Ward, 1997). Generally, the intermittent noise produces a lower threshold shift because the ear recovers from fatigue during the periods of quiet between the exposures (Figure D. 4).

Intermittent noise is likely to be a common form of anthropogenic noise to which marine mammals in the Antarctic are exposed (e.g. air-guns, sonars). Unfortunately, only four studies have investigated the relationship between noise intermittency and TTS in marine mammals and these were limited to two species, the harbor porpoise and the bottlenose dolphin (Mooney et al., 2009a; Finneran et al., 2010b; Kastelein et al., 2014b; Kastelein et al., 2015a). The limited data on the relationship between signal intermittency and TTS makes predicting TTS following exposure to intermittent underwater noise difficult and uncertain. Multiple predictive models of TTS resulting from repetitive/intermittent noise exposures have been proposed (Humes et al., 1988; Humes and Jesteadt, 1991; Department of the Navy (Don), 2001b; Southall et al., 2007; U.S. Department of the Navy, 2008; Finneran et al., 2010b; Finneran, 2015), but the lack of data has prevented adequate model validation. In general, it can be concluded that models that do not account for the recovery of the ear demonstrate the greatest over-estimates of TTS due to intermittent noise exposures.

Figure D. 4: Change in TTS as a function of noise exposure intermittency. For a noise of constant Lp, TTS will increase with increasing SEL (e.g. single 16-s exposure vs. single 64-s exposure, which has a 6 dB greater SEL). If the cumulative SEL of two noise exposures is the same, but one exposure is interrupted by quiet intervals, the TTS will be lower in the exposure with the quiet intervals (e.g. single 64-s exposure vs. four intermittent exposures of 16-s each). (X – time of noise exposure)



Source: Author’s own.

Upon cessation of exposure to narrowband or tonal noise, recovery from TTS can crudely be described as a function of the logarithm of time with recovery rates becoming more variable as recovery time increases. Reported recovery rates range from ~4 to 23 dB/decade of time (Nachtigall et al., 2004; Finneran et al., 2007; Mooney et al., 2009b; Kastelein et al., 2012b; Kastelein et al., 2012a; Kastelein et al., 2013a; Popov et al., 2014; Kastelein et al., 2019b; Kastelein et al., 2019a; Reichmuth et al., 2019; Kastelein et al., 2020a; Kastelein et al., 2020d) and generally increase as the initial TTS increases. Recovery may show two phases with different recovery rates depending upon the magnitude of the initial threshold shift (Finneran, 2015); up to three phases have been observed in terrestrial mammals with much larger shifts than obtained in marine mammal studies (Salvi and Boettcher, 2008), as well as in one harbor seal (Reichmuth et al., 2019). Although a synthesized model of TTS recovery in marine mammals has been proposed (see below), a large amount of uncertainty exists due to differences in study protocols, fatiguing stimuli, and inter-subject and inter-species variability. The large predictive errors that occur when summarizing across species (see Figure D. 6) make predicting the duration of impact to a specific marine mammal experiencing TTS challenging.

D.6.1 Relevance to Antarctic species

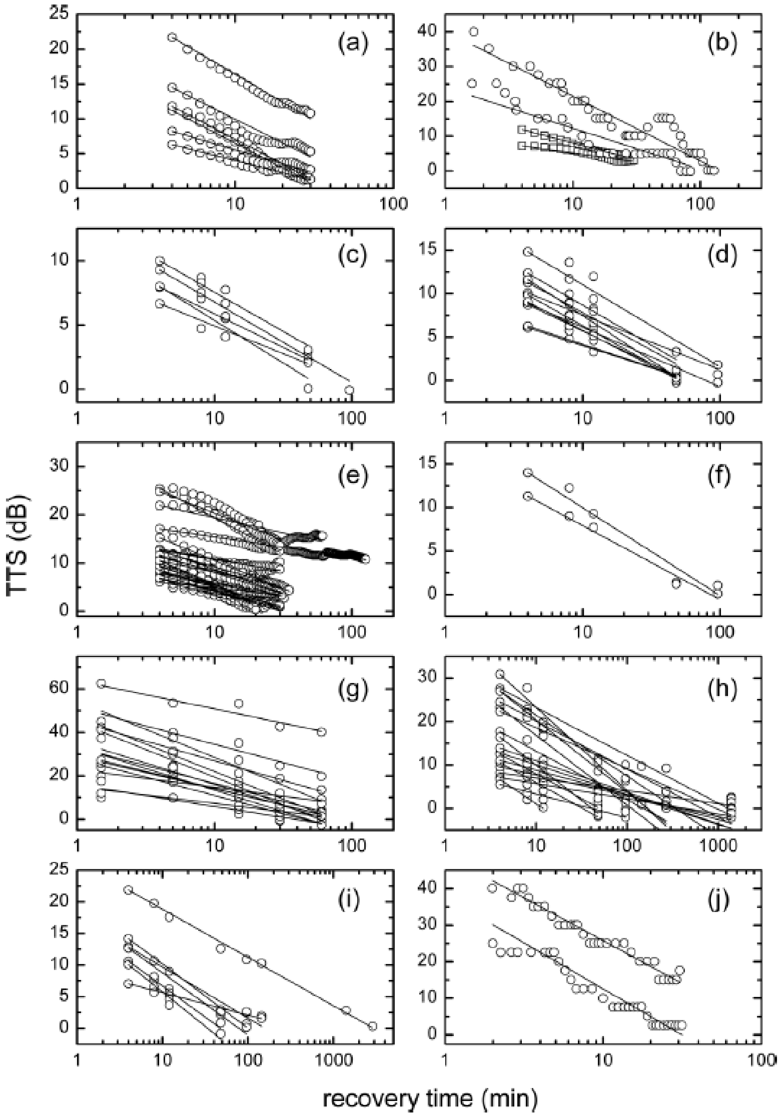
How recovery and intermittency are accounted for in predictions of impact to Antarctic species can range widely. In the most conservative approach, no recovery and no reduction in auditory fatigue due to intermittency are accounted for. Presuming TTS thresholds are exceeded, the result of this approach would likely overestimate TTS since SEL would continue to accumulate without recovery between exposures. A reset time would need to be employed to ensure that animals do not accumulate acoustic energy in perpetuity. Southall et al. (2007) originally proposed a 24-hr period over which accumulation would occur, but later revised their recommendations (Southall et al., 2019) because of data that emerged on the effects of exposure intermittency and recovery on TTS. No specific period was specified; rather, it was noted that a 24-hr rule was likely too long for most exposures and that the nature of the noise exposure and the species involved should be considered.

The rate of recovery from TTS will vary as a function of TTS magnitude, subject, and species tested, but a means for making a first approximation of recovery has been proposed. Finneran (2015) created a model of recovery based on an assumed TTS measured four minutes after the final exposure of an animal exposed to continuous noise (Figure D. 5). The log-linear model provided a reasonable prediction of recovery rates and improved when species-specific data were used for determining model parameter values (Figure D. 6). However, it was found to have limited capability for long time values and assumed that the conditions that led to TTS were independent of recovery, which has been shown to be incorrect for human data (Melnick, 1991). Furthermore, the model was not validated against TTS from impulsive signals. Nevertheless, the incorporation of TTS recovery in noise-exposed Antarctic marine mammals could provide a more accurate estimate of the tradeoff between exposure and recovery, particularly since the proposed models have shown reasonable TTS recovery rate predictions for mild to moderate TTS.

D.7 Permanent Threshold Shift

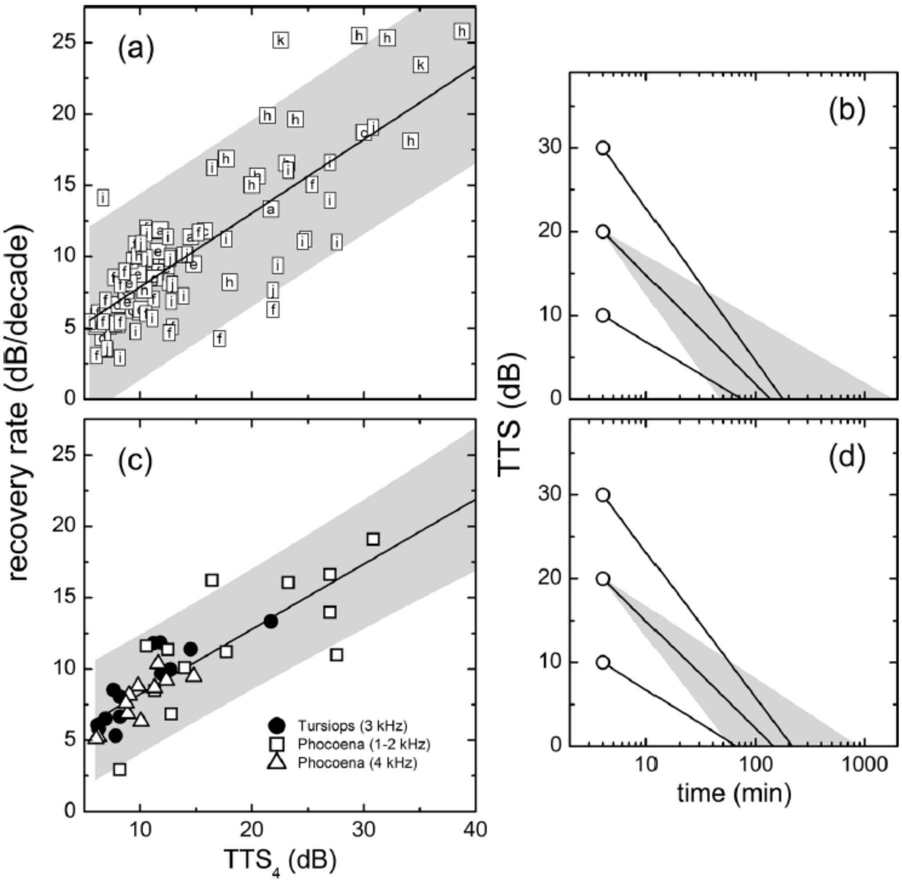
Because of the ethical issue of causing permanent injury to a marine mammal, no intentional studies of PTS have been performed in marine mammals. However, an accidental PTS occurred in a harbor seal exposed to a tonal signal of 4.1 kHz (Reichmuth et al., 2019). The seal showed an initial threshold shift >47 dB at 5.8 kHz (1/2-octave higher than the stimulus frequency) after being exposed to a 60-s tone underwater (received Lp=181 dB re 1 µPa; SEL=199 dB re 1 µPa2s). Hearing at 4.1 kHz fully recovered within 48 hrs, but 8-10 dB of NIHL persisted at 5.8 kHz. This PTS has remained over ten years after the exposure. Although this singular incident provides insight on the potential for PTS, studies to intentionally cause PTS in marine mammals are improbable and ethically problematic.

Figure D. 5: **Examples of recovery from TTS illustrating the exponential relationship between TTS and recovery time. Solid lines indicate linear best-fits to the TTS values as a function of recovery time. (a) Dolphins exposed to 3-kHz tones (Finneran et al., 2010a); (b) squares: dolphin exposed to intermittent 3-kHz tones (Finneran et al., 2010b), circles: belugas exposed to half-octave noise centered at 32-kHz (Popov et al., 2011b); (c) harbor seals exposed to octaveband noise at 4 kHz (Kastelein et al., 2012a); (d) harbor porpoise exposed to octave-band noise at 4 kHz (Kastelein et al., 2012b); (e) dolphins exposed to 3 to 56.6 kHz tones (Finneran and Schlundt, 2013); (f) harbor porpoise exposed to a 1.5-kHz tone (Kastelein et al., 2013b); (g) belugas exposed to half-octave noise at 11.2 to 90 kHz (Popov et al., 2013); (h) harbor porpoise exposed to 1–2 kHz tones (Kastelein et al., 2014a); (i) harbor porpoise exposed to 6.5-kHz tones (Kastelein et al., 2014b); (j) belugas exposed to 22.5-kHz. half-octave noise (Popov et al., 2014).**



Source: Reproduced from [Finneran, J.J., 2015. Noise-induced hearing loss in marine mammals: A review of temporary threshold shift studies from 1996 to 2015. J. Acoust. Soc. Am. 138(3), 1702-1726.], with the permission of the Acoustical Society of America.

Figure D. 6: When a linear-log function is fit to the recovery data in Fig. 5, the best-fit values for the recovery rate increase linearly with TTS4 (TTS measured 4 minutes after exposure). (a) Using all data from Fig. 5, the high dispersion in the data results in a large 95% prediction interval for the fit (shaded region). (b) Predictions for recovery from TTS4 values of 10, 20, and 30 dB (see Finneran 2015 for equations). The shaded region shows the 95% prediction interval for recovery from a TTS4 of 20 dB. The large scatter in the recovery rates in (a) results in high uncertainty in the recovery patterns, especially for larger values of recovery time. The uncertainties in the recovery patterns are lowered by examining a subset of the data, where exposure and test parameters are similar. (c) Recovery rates for only the dolphin and harbor porpoise data with exposure frequencies between 1 and 4 kHz exhibit less dispersion and smaller prediction bands for the best linear fit. (d) Predictions for recovery from TTS4 values of 10, 20, and 30 dB (see Finneran 2015 for equations). The smaller standard errors result in smaller prediction bands for the TTS recovery functions. Auditory weighting and predictions of hearing insult.



Source: Reproduced from [Finneran, J.J., 2015. Noise-induced hearing loss in marine mammals: A review of temporary threshold shift studies from 1996 to 2015. J. Acoust. Soc. Am. 138(3), 1702-1726.], with the permission of the Acoustical Society of America.

Auditory weighting functions (AWF) account for frequency-specific sensitivity of the auditory system to sound exposure. Frequencies where animals are susceptible to noise are emphasized, and frequencies where animals do not hear well are de-emphasized. This is done by adding frequency-specific values of the auditory weighting function to the noise spectral amplitude to be weighted. Weighting is done in dB and the resultant weighted noise spectral density is converted to linear units, integrated across frequency, and subsequently converted back into logarithmic units. The result is a single weighted sound level that represents the impact of frequency-specific sensitivity across the range of hearing. In regulatory practice, the weighted sound level is compared to some weighted threshold of exposure (e.g. SEL) above which an adverse impact is assumed.

Auditory weighting functions for humans are based on equal loudness contours (for review, see Houser et al., 2017), which are functions that equate the perceived loudness of tones at different frequencies to a standard (or reference) tone of fixed Lp at a fixed frequency. A number of different equal loudness contours exist because the shape of the equal loudness contour varies as a function of the L_p of the reference tone. Consequently, a number of human AWFs also exist, specifically the A-, B-, C- and D-weighting. Auditory weighting functions have been broadly used in humans ranging from use in establishing noise damage risk criteria to the prediction of annoyance due to noise exposure. In contrast, AWFs for marine mammals have only been formally adopted in the US and only for the prediction of NIHL (National Marine Fisheries Service, 2016). Marine mammal AWFs are not rooted in equal loudness contour data, but are rooted in marine mammal NIHL studies and hearing curves, largely because of the history of using NIHL as a measure of impact in the US.

The first regulatory use of AWFs to predict noise impacts was during US Navy ship-shock trials (Department of the Navy, 1998; Department of the Navy (Don), 2001a). These were the simplest of AWFs, sometimes referred to as “brick wall” filters. These earliest AWFs only considered the impact of sounds >10 Hz for mysticete whales and >100 Hz for odontocete whales. Other species of marine mammals (e.g. pinnipeds and sirenians) were not considered. In 2007, Southall et al. (2007) proposed a new set of marine mammal AWFs, or “M-weighting functions,” which were based on the human C-weighting function. The M-weighting functions reflected the human C-weighting function pattern but were altered to accommodate the hearing ranges of marine mammals. Southall et al. (2007) also proposed new thresholds for impact based on more recent TTS data collected in odontocetes and pinnipeds (Kastak et al., 1999; Schlundt et al., 2000; Finneran et al., 2002; Kastak et al., 2004; Kastak et al., 2005a). This included weighted impact thresholds for impulsive and non-impulsive sound with the former having dual criteria based on either the weighted SEL of a sound exposure or the unweighted $L_{p,\mathrm{pk}}$.

Finneran and Schlundt (2011) measured equal loudness contours in a bottlenose dolphin and used these to create new AWFs. The US Navy subsequently integrated the equal loudness data with aspects of M-weighting (Finneran and Jenkins, 2012). Two types of AWFs were created. Type I AWFs were used to predict NIHL in non-cetaceans and to predict behavioral effects in all marine mammals exposed to non-impulsive sounds. This excluded sensitive species such as harbor porpoises or beaked whales. Type II AWFs were developed to predict NIHL in cetaceans. Type II functions altered the Southall et al. (2007) M-weighting functions to address frequency-specific susceptibility to TTS, which was approximated by dolphin equal latency functions (Finneran and Schlundt, 2011). Because of limitations in the data available for making the Type II functions, their application was limited to cetaceans. As before, weighted quantities were compared to new weighted thresholds based on more recent data obtained in the bottlenose dolphin, beluga, harbor porpoise, California sea lion, and harbor seal (Schlundt et al., 2000; Finneran et al., 2002; Kastak et al., 2004; Kastak et al., 2005a; Kastak et al., 2007; Lucke et al., 2009).

The US National Marine Fisheries Service developed new weighting functions in 2016 and updated them in 2018 (National Marine Fisheries Service, 2016, 2018) to account for the continuing accumulation of data on marine mammal TTS (e.g. Kastelein et al., 2012b; Kastelein et al., 2012a; Finneran and Schlundt, 2013; Kastelein et al., 2013a; Popov et al., 2013; Kastelein et al., 2014b; Kastelein et al., 2014a; Popov et al., 2014; Finneran et al., 2015; Kastelein et al., 2015b; Kastelein et al., 2015a; Popov et al., 2015), hearing sensitivity (e.g. Ghoul and Reichmuth, 2014; Sills et al., 2014; Sills et al., 2015), and equal latency contours (e.g. Wensveen et al., 2014; Mulsow et al., 2015). An expert peer-review panel, other governmental agencies, and the public were permitted to comment on the process by which the functions were developed. The AWFs produced as part of the NMFS efforts are consistent with recent recommendations from the scientific community (Southall et al., 2019).

Other weighting functions have been proposed for use in marine mammal noise exposure assessment. These include the use of the inverted audiogram to weight sound exposure (Nedwell and Turnpenny, 1998; Nedwell et al., 2007; Terhune, 2013; Tougaard et al., 2015). In addition, AWFs for harbor porpoises have been proposed based on equal latency studies (Wensveen et al., 2014). In these studies, the animal’s reaction time is related to loudness (i.e., presumably, the louder the signal the shorter the reaction time). These alternate approaches have not come into common regulatory use, but the concept of weighting noise exposures to account for differences in hearing sensitivity are fairly well grounded, be it for annoyance or NIHL (e.g. temporal weighting of signals to approximate loudness perception in assessing potential behavioral responses, Tougaard and Beedholm, 2019). With respect to predicting NIHL in Antarctic species, consideration of the Southall et al. (2019) weighting function recommendations seems warranted given that the approach emphasizes frequency-specific susceptibility to NIHL and species/hearing capability groupings. If weighting were to be applied for other reasons, other weighting approaches might be more appropriate (e.g. such as weighting for behavioral response, Nedwell et al., 2007).

D.8 Other factors affecting hearing insult

Antarctic marine mammals are likely to be exposed to a combination of continuous and intermittent sources when encountering underwater anthropogenic noise since nearly all intermittent sources will be transmitted in the presence of a ship, which is a continuous noise source while under way. If the received level of both types of noise are sufficiently high, the fatiguing effects of both continuous and intermittent sources ideally would be considered synergistically. Unfortunately, how such compound noise exposures relate to TTS/PTS is unknown and how knowledge of independent processes would be combined to address this issue is likely to remain a policy decision (e.g. only the dominant source might be considered).

Impulsive signals become less impulsive as they travel away from their source. Because of absorption, refraction and scattering, the signal eventually loses the short rise time and high-pressure peak that characterizes it as an impulse. This phenomenon is most relevant to airgun arrays since at some distance from the array the airgun signal would presumably affect the ear more like a continuous-wave sound and less like an impulsive sound (Hastie et al., 2019). Presented at high enough duty cycle, repetitive airgun shots may be perceived as no different from continuous noise when received at sufficient distance from the source. Recent efforts characterizing signals based upon various metrics of “impulsiveness” and relating these metrics to a proposed “equivalent quiet” suggest that impulsive signals that have traveled sufficient distance as to lose their impulsive character are no longer a concern with respect to the potential to physiologically impair hearing (Martin et al., 2020). Such approaches, both with respect to equivalent quiet and impulse characterization warrant further investigation, particularly in relation to anthropogenic noise sources common to the Antarctic.

In determining how available TTS data might be used to inform noise impacts to Antarctic marine mammals, recent findings on the self-mitigation of noise exposure in odontocetes should be considered. Specifically, toothed whales have been shown capable of reducing their hearing sensitivity by >10 dB when a high-level sound exposure is expected (Nachtigall and Supin, 2013, 2014; Nachtigall and Ya Supin, 2015; Nachtigall et al., 2016b; Nachtigall et al., 2016a; Finneran, 2018). Finneran et al. (2015) also observed dolphins anticipate airgun exposures and alter their orientation to the sound source just prior to an airgun shot. Whether this also corresponded to a reduction in hearing sensitivity is uncertain, but the knowledge that toothed whales can decide to change hearing sensitivity and anticipate sound exposures complicates the interpretation of all TTS studies involving toothed whales. It cannot be stated with certainty that odontocetes engaged in TTS studies did not decrease their hearing sensitivity if experimental paradigms provided unintentional cues to impending sound exposure. On one hand, this might be concerning if some or all TTS data collected to date reflect TTS of an animal that had already reduced its hearing sensitivity. In the wild, an animal may not change its sensitivity, particularly if it is the first of an unexpected sound exposure. In such a scenario, it seems feasible that the threshold of impact might be lower. On the other hand, given the rapidity with which toothed whales seem capable of changing the hearing sensitivity (on the order of seconds), it seems like any unexpected noise exposure could be quickly mitigated after the first or second noise emission or if the noise source is first perceived at a lower level (e.g. approaching seismic vessel).

Differences in individual susceptibility to NIHL have long been known in the human and animal world and have been observed even when individuals have been kept under controlled living conditions (e.g. Davis et al., 2003). Although the data are limited, a few observations suggest differences in the onset and growth of TTS also exist in marine mammals. For example, compare the onset or growth of TTS between subjects reported in Kastelein et al. (2012b; 2020a) and Popov et al. (2013). Thresholds for TTS in marine mammals are typically derived from some measure of central tendency, potentially grouped across individuals from different species (but with some sort of phylogenetic grouping). The real world is likely not so simply described and it is expected that variation in NIHL susceptibility within marine mammals exists. Indeed, some modeling efforts have attempted to incorporate variability into NIHL predictions (Gedamke et al., 2011). However, until a more substantial body of empirical information on the complex relationships between frequency, L_p, and duration of sound exposure are obtained across individuals, estimates of the magnitude of variation in NIHL susceptibility will likely need to be drawn from terrestrial and laboratory animal data.

D.9 TTS and the injury debate

The potential for TTS to be associated with the destruction of tissue is based on work in laboratory animals. Kujawa and Liberman (2009) showed that a ~40 dB TTS in mice measured 24-hours after the noise exposure with AEP methods produced acute loss of afferent nerve terminals (synaptopathy) and degeneration of the cochlear nerve that did not manifest until weeks after the exposure, even though hearing thresholds returned to normal days to weeks after the exposure. Additional work with laboratory animals has supported these findings (Lin et al., 2011; Wang and Ren, 2012). As a result of evidence that threshold shifts could recover in light of permanent damage to the auditory system, whether or not TTS should be considered injurious in marine mammals has been discussed (e.g. Tougaard et al., 2015).

PTS can occur due to high level sound exposures (e.g. explosions) that result in near immediate mechanical disruption of hair cell stereociliary arrays, damage to the organ of Corti, breakage of the reticular lamina, or extensive disruption of the endolymphatic compartment (Ohlemiller, 2008; Kurabi et al., 2017). At less extreme exposures, PTS occurs primarily through hair cell loss that is biochemically mediated. This occurs through the intracellular production of reactive oxygen and nitrogen species (ROS and RNS, respectively) and alteration of protein kinase pathways that can trigger apoptosis or necroptosis (Kurabi et al., 2017; Le et al., 2017). In all cases, there is little argument against PTS resulting from damage to cellular and tissue components of the auditory system. Mechanisms contributing to TTS include metabolic overstimulation, the activation or disruption of various ion channels, temporary uncoupling of the tectorial membrane and outer hair cells, and excitotoxicity-driven swelling of afferent terminals with inner hair cells (Kurabi et al., 2017; Le et al., 2017). The mechanisms of PTS and TTS are not necessarily mutually exclusive, and there are certainly shared processes that produce different outcomes based upon the degree of overstimulation of the ear (e.g. the degree of ROS production). The probability of whether tissue destruction occurs also likely increases with the degree of ear overstimulation (acoustic exposure) and it is probable that repeat exposures, each capable of causing a substantial threshold shift, might result in tissue destruction if complete recovery has not occurred between exposures (e.g. Wang and Ren, 2012).

To reconcile the findings of the TTS literature demonstrating tissue damage with the TTS work performed in marine mammals, there must first be an understanding of the magnitude of threshold shifts achieved in laboratory animal work and the time courses at which shifts were measured. Initial threshold shifts to which tissue damage have been associated in laboratory animals range from ~35-50 dB of TTS (e.g. Kujawa and Liberman, 2009; Lin et al., 2011; Wang and Ren, 2012). Initial shifts in these studies were measured 24-hrs post-exposure and the measurements were made using AEPs. The majority of marine mammal TTS studies have behaviorally measured smaller amounts of TTS (<15 dB) within minutes of noise exposure. As previously noted, threshold shifts in noise-exposed bottlenose dolphins measured with AEPs were 19-33 dB higher than those determined behaviorally (Finneran et al., 2007). If the difference between the magnitude of AEP and behavioral threshold shifts measured following noise exposure is consistent across marine mammals, then the modest behaviorally-measured threshold shifts reported in marine mammal studies could fall within the magnitude of AEP shifts observed in laboratory animals that have been associated with tissue damage. However, as previously noted, the initial TTS measurements in marine mammal studies are typically made within minutes of noise exposure, *not 24-hrs after the exposure as conducted in laboratory animals*. Given the recovery of the ear from TTS following noise exposure (see section D.6), TTS measured within minutes of the noise exposure would be much higher than that measured 24-hrs after the exposure. Comparisons between laboratory animal studies with 24-hr post-exposure TTS measures and marine mammal studies made within minutes of exposure cessation must keep this difference in mind, particularly since most marine mammal TTS studies show recovery to baseline thresholds within 24 hrs of noise exposure even when TTS measured behaviorally and immediately following the noise exposure is as high as ~30 dB.

The relationship between the magnitude of TTS and tissue damage is uncertain in marine mammals, and little information exists on it in terrestrial mammals. However, a limited amount of work in mice demonstrates that there exists both neuropathic and non-neuropathic levels of TTS. In-air octave-band (8-16 kHz) noise exposures in mice ranging from 91-100 dB SPL (dB re 20 µPa) for periods of two hours demonstrated significant synaptopathy at exposures > 97 dB, but not for exposures < 94 dB (Hickox and Liberman, 2014; Fernandez et al. 2015; Jensen et al. 2015). The degree of synaptopathy was progressive and frequency-dependent, i.e. the degree of synaptopathy varied as a function of the cochlear frequency-place map. The magnitude of TTS measured after noise exposure ranged from ~50 dB measured 6 hrs after exposure to ~35-40 dB measured 24 hrs after exposure in non-neuropathic mice, showing substantial TTS could occur without the presence of synaptopapthy. The onset of synaptopathy occurred over exposures that differed by as little to 6-9 dB from those that were non-neuropathic suggesting a narrow range over which the onset and dramatic growth of synaptopathy occurs. Thus, the limited evidence available in laboratory animals suggests that TTS can occur without tissue damage, but that damage does occur at some point as sound exposure (and TTS) increase.

It is probable that threshold shifts in marine mammals can occur with noise exposures that range in magnitude and effect from fully recoverable TTS without tissue damage, through fully recoverable TTS with tissue damage, to the destruction of tissue producing PTS. Therefore, even though it has been demonstrated that TTS of sufficient magnitude can result in underlying tissue damage (Kujawa and Liberman, 2009), the implementation of regulatory thresholds based on the onset of TTS should capture the onset of recoverable auditory fatigue without the occurrence of tissue damage (e.g. see Le Prell 2019 for review).

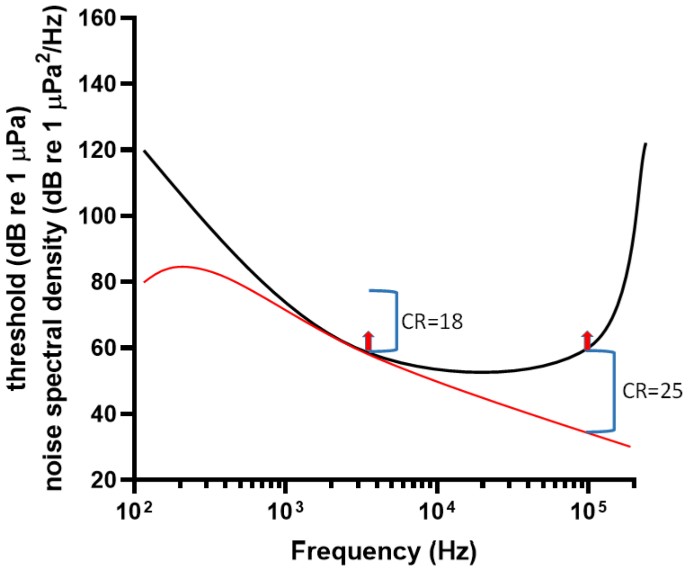
D.10 When does hearing loss matter?

It is not uncommon to hear the argument that PTS is injury (and arguably some degree of TTS) and should therefore be mitigated. But when does hearing loss truly become impactful to an animal, and when might it be inconsequential? From a fitness perspective, hearing loss is consequential when it affects some aspect of the animal's ability to survive, acquire resources, or reproduce. Therefore, if an animal suffers a sufficient hearing loss so as to affect one of these life functions, then it incurs a possible fitness cost to the animal. These costs can subsequently accumulate across populations to manifest as population-level consequences (e.g. King et al., 2015).

The magnitude of the shift and the frequency (or frequencies) at which a NIHL occurs are important considerations for the impact that the shift might have on an animal. The critical ratio (CR), which is the ratio of a tone's signal power and the power spectral density (PSD; dB re 1 µPa^2/Hz) of broadband white noise at the tone's detection threshold, has been used in conjunction with the power spectrum model of hearing to predict masking in marine mammals (for review, see Erbe et al., 2016). It can similarly be used to predict whether a NIHL is consequential by comparing the shifted hearing threshold with the frequency-specific CR and the PSD of environmental noise surrounding the affected frequency of hearing. As an example, assume a 6 dB TTS in a hypothetical marine mammal. Two scenarios are given – one in which the animal suffers a 6 dB TTS at a hearing frequency centered at 3 kHz and another where the shift occurs at a hearing frequency of 100 kHz (see Figure D. 7). At both frequencies, the hypothetical animal's normal (unshifted) threshold of hearing is 60 dB; once shifted, the animal has a new "temporary" hearing threshold of 66 dB. The CRs for 3 kHz and 100 kHz are 18 dB and 25 dB, respectively, and the PSD of environmental noise around the frequencies of interest are 60 dB and 35 dB re 1 µPa^2/Hz, respectively. Given the environmental noise near 3 kHz, a 3-kHz signal would need to be at least 78 dB L_p (and long enough that temporal summation has not affected the threshold (e.g. Holt et al., 2012) for it to be detectable (18 dB (CR) + 60 dB noise PSD) under normal circumstances. In this particular instance, the animal's normal hearing threshold (60 dB) and the shifted threshold (66 dB) are both less than the signal level required for detection due to noise, i.e. signal detection is noise-limited under either circumstance and the shift has no impact on the animal's signal detection ability. Conversely, at 100 kHz, the received signal level would need to be just above 60 dB L_p under normal hearing conditions to be detected (25 dB (CR) + 35 dB noise PSD). This equates to the animal's hearing threshold so signal detection is not noise-limited. However, once the TTS has occurred, the received signal would have to be at least 6 dB stronger to be detected. Signal detection would therefore be limited by the animal's hearing sensitivity, the threshold shift would reduce the ability to detect a 100-kHz signal, and the animal's acoustic space in which it operates (with respect to 100-kHz signals) would be reduced accordingly. Thus, interpreting the impact of a threshold shift must consider the background noise of the habitat used by the animal as well as the animal's ability to detect an acoustic signal in noise.

To fully evaluate how a NIHL might impact the fitness of a marine mammal, other aspects of the animal's biology must be considered. Signal discrimination requires a higher signal excess than signal detection and is critical to animal responsiveness (Erbe et al., 2016); thus, the impact of any threshold shift should give thought to the impact both on the animal's signal discrimination and detection capability. Whether or not the frequencies affected by a NIHL have particular utility to the animal also requires consideration. Frequencies used for communication, foraging (e.g. echolocation or passive prey localization), or listening for predators would be of greater importance than frequencies that are not relied upon for purposes of survival or reproduction. The impact must be gauged according to the magnitude of the shift; a 6 dB threshold shift is a small reduction in hearing sensitivity and should not be treated equivalently to a much larger shift (e.g. 40 dB) that could significantly impact the ability of an animal to detect and discriminate sounds. Obviously, the duration of the NIHL also needs to be considered. Evidence to date suggests that an initial TTS of 6 dB, as used in the example, would likely recover within minutes of occurring (for review see Finneran, 2015). Such short time frames might have little impact on an animal's ability to acquire energy, avoid predators, find mates, etc. A larger TTS would take longer to recover, potentially days, with the magnitude of impact to signal detection and discrimination declining with the time post-exposure. On the other hand, a PTS would not recover but its impact would nevertheless need to be considered in context of the other aforementioned points.

Figure D. 7: **Demonstration of the interaction of environmental noise level and animal hearing abilities on the consequences of a threshold shift. The black curve corresponds to the hypothetical animal audiogram and the red curve corresponds to the environmental noise PSD. Thresholds at 3 kHz and 100 kHz are both 60 dB re 1 µPa, but the critical ratios (CR) are 18 and 25 dB, respectively. The tips of the red arrows denote a 6 dB threshold shift at each of the frequencies. At 3 kHz, signal detection remains noise limited after the threshold shift as a signal of 78 dB Lp (18 dB (CR) + 60 dB noise PSD) would be required for detection. Conversely, at 100 kHz, signal detection is limited by the animal's hearing sensitivity (i.e. the shifted threshold) since the sensitivity is less (threshold is greater) than limitations imposed by the environmental noise and CR.**



Source: Author's own.

D.11 Conclusion

Stewardship of the Antarctic is the responsibility of all nations that utilize the Antarctic. The introduction of anthropogenic noise into the Southern Ocean is one of many potential impacts from human use and exploration of the Antarctic. Management and protection of the Southern Oceans marine mammals do not fall to any single country; consideration of the potential impact of anthropogenic noise and its mitigation and regulation should be considered by all. Noise impacts to the hearing ability of Antarctic marine mammals, whether it be temporary or permanent and whether or not it is associated with underlying tissue damage, should be predicted using the best available science and mitigated using science-based approaches and appropriate conservation principles. Because no studies of NIHL have been conducted on any Antarctic marine mammals, data used for hearing impact predictions must necessarily rely on surrogate species for which data exist. Nevertheless, certain approaches with a longstanding history of use and established scientific basis and which account for species-specific hearing capabilities and sensitivities to noise exposure, such as the auditory weighting functions proposed by Southall et al. (2019), should be considered in order to provide practical predictions. Ideally, the hearing impacts that are predicted should be related to fitness consequences so that procedures mitigating population-level impacts can be balanced with exploration needs.

D.12 Appendix to Annex 4

D.12.1 Details of data sources in Annex 4

Table D. 6: Subject, exposure, and hearing test parameters used in the various marine mammal TTS studies. Sp: species, Pv: *Phoca vitulina*, Zc: *Zalophus californianus*, Ma: *Mirounga angustirostris*, Tt: *Tursiops truncatus*, Dl: *Delphinapterus leucas*, Pp: *Phocoena phocoena*, Np: *Neophocaena phocaenoides asiaeorientalis*, Pl: *Phoca largha*, Ph: *Phoca hispida*; BBN: broadband noise, OBN: octave-band noise, HOBN: half-octave band noise, SOBN: sixth-octave band noise, Sim MFAS: simulated midfrequency active sonar, DC: duty cycle, INT: intermittent, CW: continuous, PT: pure tone, AM: amplitude modulated, FM: frequency modulated, Rev: AEP threshold based on reversals (i.e., lowest detachable response), Reg: threshold based on linear regression to arbitrary response amplitude. (Reproduced from [Finneran, J.J., 2015. Noise-induced hearing loss in marine mammals: A review of temporary threshold shift studies from 1996 to 2015. J. Acoust. Soc. Am. 138(3), 1702-1726], with the permission of the Acoustical Society of America. Note – the table has been updated with studies conducted since the original publication date of 2015.)

Study	Subjects				Exposure								Hearing Test					
	Sp	Age	Sex	Name	Medium	Type	DC	Frequency (kHz)	Duration	SPL (dB)	Controls	Signal Type	Signal Frequency (kHz)	Signal Duration (ms)	Procedure	Method	Environment	Recovery
(Kastak and Schusterman, 1996)	Pv	4	M	Sprouts	Air[22]	BBN	INT	between 0.025-0.16 and 1.6-10	6 days	90-105	N	PT	0.1	500	Staircase	Behav.	Ambient (air)	1 week
(Kastak et al., 1999)	Pv	10	M	Sprouts	Water	OBN	CW	0.1	20 min	~133-156 (est)	Y	PT	0.1	500	Staircase	Behav.	Pool	6-10 min, 24 h

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[22] noise source in air but subject underwater

Study	Subjects				Exposure								Hearing Test					
	Sp	Age	Sex	Name	Medium	Type	DC	Frequency (kHz)	Duration	SPL (dB)	Controls	Signal Type	Signal Frequency (kHz)	Signal Duration (ms)	Procedure	Method	Environment	Recovery
(Kastak et al., 1999)	Zc	12	F	Rio	Water	OBN	CW	0.5	20 min	~123-140 (est)	Y	PT	0.5, 0.75, 1	500	Staircase	Behav.	Pool	6-10 min, 24 h
(Kastak et al., 1999)	Zc	21	F	Rocky	Water	OBN	CW	1	20 min	~134-161 (est)	Y	PT	1	500	Staircase	Behav.	Pool	6-10 min, 24 h
(Kastak et al., 1999)	Ma	4	F	Burnyce	Water	OBN	CW	1	22 min	~144-149 (est)	Y	PT	1	500	Staircase	Behav.	Pool	6-10 min, 24 h
(Schlundt et al., 2000)	Tt	12-14	F	APR	Water	Tone	CW	3	1 s	160-202	N	PT	3, 4.5, 6	250	Staircase	Behav.	SD Bay+ masking noise	1-3 min, 5-20 min, 60-300 min
(Schlundt et al., 2000)	Tt	33-35	M	BEN	Water	Tone	CW	10 20 20 3 0.4	1 s	179-202	N	PT	10, 15, 20 20, 30, 40 30 4.5	250	Staircase	Behav.	SD Bay+ masking noise	1-3 min, 5-20 min, 60-300 min

Study	Subjects				Exposure								Hearing Test					
	Sp	Age	Sex	Name	Medium	Type	DC	Frequency (kHz)	Duration	SPL (dB)	Controls	Signal Type	Signal Frequency (kHz)	Signal Duration (ms)	Procedure	Method	Environment	Recovery
													0.6					
(Schlundt et al., 2000)	Tt	19-21	F	MUU	Water	Tone	CW	20	1 s	160-197	N	PT	20, 30, 40	250	Staircase	Behav.	SD Bay+ masking noise	1-3 min, 5-20 min, 60-300 min
(Schlundt et al., 2000)	Tt	31-33	M	NEM	Water	Tone	CW	75 3 10 20 20 3 0.4	1 s	160-202	N	PT	75, 85, 100 3, 4.5, 6 10, 15, 20 20, 30, 40 30 4.5 0.6	250	Staircase	Behav.	SD Bay+ masking noise	1-3 min, 5-20 min, 60-300 min

Study	Subjects				Exposure								Hearing Test					
	Sp	Age	Sex	Name	Medium	Type	DC	Frequency (kHz)	Duration	SPL (dB)	Controls	Signal Type	Signal Frequency (kHz)	Signal Duration (ms)	Procedure	Method	Environment	Recovery
(Schlundt et al., 2000)	Tt	38-40	F	TOD	Water	Tone	CW	20 75	1 s	160-197	N	PT	20, 30, 40 75, 85, 100	250	Staircase	Behav.	SD Bay+ masking noise	1-3 min, 5-20 min, 60-300 min
(Schlundt et al., 2000)	Dl	29-31	F	MUK	Water	Tone	CW	3 10 20 20 3 0.4	1 s	160-202	N	PT	3, 4.5, 6 10, 15, 20 20, 30, 40 30 4.5 0.6	250	Staircase	Behav.	SD Bay+ masking noise	1-3 min, 5-20 min, 60-300 min
(Schlundt et al., 2000)	Dl	20-22	M	NOC	Water	Tone	CW	3 10 20 20 3 0.4	1 s	160-202	N	PT	3, 4.5, 6 10, 15, 20	250	Staircase	Behav.	SD Bay+ masking noise	1-3 min, 5-20 min, 60-

Study	Subjects				Exposure								Hearing Test					
	Sp	Age	Sex	Name	Medium	Type	DC	Frequency (kHz)	Duration	SPL (dB)	Controls	Signal Type	Signal Frequency (kHz)	Signal Duration (ms)	Procedure	Method	Environment	Recovery
													20, 30, 40 30 4.5 0.6					300 min
(Finneran et al., 2000)	Tt	35	M	BEN	Water	Impulse	Single	broadband	5-13 ms	up to 221 (p-p)	N	PT	1.2, 1.8, 2.4	250	Staircase	Behav.	SD Bay+ masking noise	2-3 min, 5-15 min, 1-1.5 h,
(Finneran et al., 2000)	Tt	33	M	NEM	Water	Impulse	Single	broadband	5-13 ms	up to 221 (p-p)	N	PT	1.2, 1.8, 2.4	250 `	Staircase	Behav.	SD Bay+ masking noise	2-3 min, 5-15 min, 1-1.5 h,
(Finneran et al., 2000)	Dl	31	F	MUK	Water	Impulse	Single	broadband	5-13 ms	up to 221 (p-p)	N	PT	1.2, 1.8, 2.4	250	Staircase	Behav.	SD Bay+ masking noise	2-3 min, 5-15 min, 1-1.5 h,

Study	Subjects				Exposure								Hearing Test					
	Sp	Age	Sex	Name	Medium	Type	DC	Frequency (kHz)	Duration	SPL (dB)	Controls	Signal Type	Signal Frequency (kHz)	Signal Duration (ms)	Procedure	Method	Environment	Recovery
(Finneran et al., 2002)	Tt	36	M	BEN	Water	Impulse	Single	broadband	10–14 ms	215-228 (p-p)	Y	PT	0.4, 4, 30	250	Staircase	Behav.	SD Bay+ masking noise	2 min, 4 min, 10 min
(Finneran et al., 2002)	Dl	32	F	MUK	Water	Impulse	Single	broadband	6-20 ms	202-228 (p-p)	Y	PT	0.4, 4, 30	250	Staircase	Behav.	SD Bay+ masking noise	2 min, 4 min, 10 min
(Finneran et al., 2003)	Zc	19	M	NRT	Water	Impulse	Single	broadband	10–20 ms	160-205 (p-p)	Y	PT	1, 10	250	Staircase	Behav.	SD Bay+ masking noise	5 min, 10 min
(Finneran et al., 2003)	Zc	23	M	LIB	Water	Impulse	Single	broadband	10–20 ms	183-201 (p-p)	Y	PT	1, 10	250	Staircase	Behav.	SD Bay+ masking noise	5 min, 10 min
(Nachtigall et al., 2003)	Tt	12	M	Boris	Water	BBN	CW	4–11	30–55 min	up to 179	N	PT	7.5	3000	Staircase	Behav.	Kaneohe Bay	10-20 min, 45 min, 1.5, 3, 6h

Study	Subjects				Exposure								Hearing Test					
	Sp	Age	Sex	Name	Medium	Type	DC	Frequency (kHz)	Duration	SPL (dB)	Controls	Signal Type	Signal Frequency (kHz)	Signal Duration (ms)	Procedure	Method	Environment	Recovery
(Nachtigall et al., 2004)	Tt	13	M	Boris	Water	BBN	CW	4–11	30–55 min	160	Y	AM	8, 11.2, 16, 22.5, 32	20	Reg	AEP	Kaneohe Bay	5, 10, 15, 25, 45, 105 min
(Finneran et al., 2005)	Tt	38-40	M	BEN	Water	Tone	CW	3	1, 2, 4, 8 s	up to 200	Y	PT	3, 4.5	500	Staircase	Behav.	Pool	4 min, 10 min
(Finneran et al., 2005)	Tt	18-20	M	NAY	Water	Tone	CW	3	1, 2, 4, 8 s	up to 200	Y	PT	3, 4.5	500	Staircase	Behav.	Pool	4 min, 10 min
(Kastak et al., 2005)	Pv	14	M	Sprouts	Water	OBN	CW	2.5	22-50 min	137, 152	Y	PT	2.5, 3.53	500	Staircase	Behav.	Pool	<15 min, 24 h
(Kastak et al., 2005)	Zc	16	F	Rio	Water	OBN	CW	2.5	22-50 min	159, 174	Y	PT	2.5, 3.53	500	Staircase	Behav.	Pool	<15 min, 24 h
(Kastak et al., 2005)	Ma	7	F	Burnyce	Water	OBN	CW	2.5	22- 50 min	149, 164	Y	PT	2.5, 3.53	500	Staircase	Behav.	Pool	<15 min, 24 h

Study	Subjects				Exposure								Hearing Test					
	Sp	Age	Sex	Name	Medium	Type	DC	Frequency (kHz)	Duration	SPL (dB)	Controls	Signal Type	Signal Frequency (kHz)	Signal Duration (ms)	Procedure	Method	Environment	Recovery
(Finneran et al., 2007)	Tt	41	F	BLU	Water	Tone	CW INT	20 20	64 s 3 × 16 s	185 193	Y	FM, AM	10, 20, 30, 40, 50, 60, 70	500	Y	FM, AM	10, 20, 30, 40, 50, 60, 70	4-30 min, 1-2 h, 1, 4, 5 days
(Kastak et al., 2007)	Zc	17-20	F	Rio	Air	OBN	CW	2.5	1.5-50 min	94-133	Y	PT	2.5	500	Staircase	Behav.	Anechoic Chamber	10-15 min, 24h +
(Kastak et al., 2008)	Pv		M	Sprouts	Water	Tone	CW	4.1	60 s (max)	up to 184	Y	PT	5.8	500	Staircase	Behav.	Pool	up to 2 months
(Lucke et al., 2009)	Pp	9-10	M	Eigil	Water	Impulse	Single	broadband	~0.1 s	~160-202 (p-p)	N	AM	4, 32, 100	25	Rev	AEP	Kerteminde Harbor	up to 2000 min
(Mooney et al., 2009b)	Tt	18	M	Boris	Water	OBN	CW	5.6 (center)	1.9, 3.8, 5.6, 7.5, 15, 30 min	160-178	Y	AM	5.6, 8, 11.2, 16, 22.5	20	Reg	AEP	Kaneohe Bay	5, 10, 20, 40, 80 min

Study	Subjects				Exposure								Hearing Test					
	Sp	Age	Sex	Name	Medium	Type	DC	Frequency (kHz)	Duration	SPL (dB)	Controls	Signal Type	Signal Frequency (kHz)	Signal Duration (ms)	Procedure	Method	Environment	Recovery
(Mooney et al., 2009a)	Tt	18	M	Boris	Water	Sim. MFAS	INT	~ 3 kHz fundamental	3×1 s	up to 203	Y	AM	5.6	20	Reg	AEP	Kaneohe Bay	5, 10, 20, 40 min
(Finneran et al., 2010a)	Tt	38-40	F	BLU	Water	Tone	CW	3	8, 16, 32, 64, 100, 128 s	~140 -200	Y	PT, FM	4.5	500	Staircase	Behav.	Pool	4 min, 10 min, 30 min
(Finneran et al., 2010a)	Tt	25-26	M	TYH	Water	Tone	CW	3	16, 32, 64 s	~140 -189	Y	PT, FM	4.5	500	Staircase	Behav.	Pool	4 min, 10 min, 30 min
(Finneran et al., 2010b)	Tt	40	F	BLU	Water	Tone	INT	3	4 × 16 s	~192	Y	FM	4.5	500	Staircase	Behav.	Pool	4 min
(Finneran and Schlundt, 2010)	Tt	42	F	BLU	Water	Tone	CW	3, 20	16 s	128-191	Y	FM	4.5, 30	500	Staircase	Behav.	Pool	4 min

Study	Subjects				Exposure								Hearing Test					
	Sp	Age	Sex	Name	Medium	Type	DC	Frequency (kHz)	Duration	SPL (dB)	Controls	Signal Type	Signal Frequency (kHz)	Signal Duration (ms)	Procedure	Method	Environment	Recovery
(Popov et al., 2011b)	Dl	N/A	M	N/A	Water	HOBN	CW	16, 32, 45, 64 (center)	1, 3, 10, 30 min	140, 150, 160	N	pip train	45	~16	Rev	AEP	Small tank	~1–120 min
(Popov et al., 2011a)	Np	11	M	A Bao	Water	HOBN	CW	22, 32, 45, 64, 90, 128 (center)	1, 3, 10, 30 min	140, 150, 160	N	pip train	32, 45, 64, 128	~16	Rev	AEP	Small tank	~1–100 min
(Popov et al., 2011a)	Np	15	F	Ying Ying	Water	HOBN	CW	22, 32, 45, 64, 90, 128 (center)	1, 3, 10, 30 min	140, 150, 160	N	pip train	32, 45, 64, 128	~16	Rev	AEP	Small tank	~1–100 min
(Kastelein et al., 2012b)	Pv	4-5	F	Seal 01	Water	OBN	CW	4 (center)	7.5, 15, 30, 60, 120, 240 min	124, 136, 148	Y	FM	4, 5.7	1000	Rev	Behav.	Pool	4, 8, 12, 48, 96 min
(Kastelein et al., 2012b)	Pv	4-5	F	Seal 02	Water	OBN	CW	4 (center)	7.5, 15, 30, 60, 120, 240 min	124, 136, 148	Y	FM	4, 5.7	1000	Rev	Behav.	Pool	12, 48, 96 min

Study	Subjects				Exposure								Hearing Test					
	Sp	Age	Sex	Name	Medium	Type	DC	Frequency (kHz)	Duration	SPL (dB)	Controls	Signal Type	Signal Frequency (kHz)	Signal Duration (ms)	Procedure	Method	Environment	Recovery
(Kastelein et al., 2012a)	Pp	5	M	02	Water	OBN	CW	4 (center)	7.5, 15, 30, 60, 120, 240 min	124, 136, 148	Y	FM	4, 5.7	1000	Rev	Behav.	Pool	4, 8, 12, 48, 96 min
(Finneran and Schlundt, 2013)	Tt	42-44	F	BLU	Water	Tone	CW	3,5,7,10, 14,20,28,40	16 s	128-191	Y	FM	5, 7, 10, 14, 20, 28, 40, 56	500	Staircase	Behav.	Pool	4-30 min, 24 h
(Finneran and Schlundt, 2013)	Tt	26-28	M	TYH	Water	Tone	CW	3,40,56,80	16 s	120-189	Y	FM	5, 56, 80, 113	500	Staircase	Behav.	Pool	4-30 min, 24 h
(Kastelein et al., 2013b)	Pp	7	M	02	Water	Tone	CW	1.5	60 min	154	Y	FM	1.5, 2, 4, 6.5, 8, 16, 32, 63, 125	1000	Rev	Behav.	Pool	4, 8, 12, 48, 96 min

Study	Subjects				Exposure								Hearing Test					
	Sp	Age	Sex	Name	Medium	Type	DC	Frequency (kHz)	Duration	SPL (dB)	Controls	Signal Type	Signal Frequency (kHz)	Signal Duration (ms)	Procedure	Method	Environment	Recovery
(Kastelein et al., 2013a)	Pv	4-5	F	Seal 02	Water	OBN	CW	4 (center)	60 min	163	Y	FM	4	1000	Rev	Behav.	Pool	12 min to 10 days
(Popov et al., 2013)	Dl	2	M	N/A	Water	HOBN	CW	11, 22, 45, 90 (center)	1, 3, 10, 30 min	165	N	pip train	8-128	~16	Rev	AEP	Small tank	1-60 min
(Popov et al., 2013)	Dl	2	F	N/A	Water	HOBN	CW	11, 22, 45, 90 (center)	1, 3, 10, 30 min	165	N	pip train	8-128	~16	Rev	AEP	Small tank	1-60 min
(Kastelein et al., 2014)	Pp	7	M	02	Water	FM sweep	CW, 0.75, 0.5, 0.375, 0.25, 0.175, 0.1, 0.05	1-2	1-s sweep, 1.9 to 240 min total duration	144-180	Y	FM	1.5	1000	Rev	Behav	Pool	4, 8, 12, 48, 96 min
(Kastelein, 2014)	Pp	8	M	02	Water	Tone	CW	6.5	60 min	118-154	Y	FM	6.5, 9.2, 13, 16, 125	1000	Rev	Behav.	Pool	4, 8, 12, 48, 96, 144 min, 1

Study	Subjects				Exposure								Hearing Test					
	Sp	Age	Sex	Name	Medium	Type	DC	Frequency (kHz)	Duration	SPL (dB)	Controls	Signal Type	Signal Frequency (kHz)	Signal Duration (ms)	Procedure	Method	Environment	Recovery
																		day, 2 days
(Popov et al., 2014)	Dl	2	M	N/A	Water	HOBN	CW	22 (center)	2 s – 100 min	150-180	N	pip train	32	~16	Reg	AEP	Small tank	2-60 min
(Popov et al., 2014)	Dl	2	F	N/A	Water	HOBN	CW	22 (center)	2 s – 100 min	150-170	N	pip train	32	~16	Reg	AEP	Small tank	2-60 min
(Finneran et al., 2015)	Tt	45-46	F	BLU	Water	10 impulses	$0.1\ s^{-1}$	broadband	~0.1–0.5 s	up to 212 (p-p)	Y	FM, AM	0.5, 1, 2, 4, 8, 16, 32, 40, 50	500 ~ 30 s	Staircase Rev/Reg	Behav. AEP	SD Bay	~2–10 min
(Finneran et al., 2015)	Tt	30-32	M	TYH	Water	10 impulses	$0.1\ s^{-1}$	broadband	~0.1–0.5 s	up to 208 (p-p)	Y	FM, AM	0.25, 0.5, 1, 2, 4, 8, 16, 32, 45, 64	500 ~ 30 s	Staircase Rev/Reg	Behav. AEP	SD Bay	~2–10 min

Study	Subjects				Exposure								Hearing Test					
	Sp	Age	Sex	Name	Medium	Type	DC	Frequency (kHz)	Duration	SPL (dB)	Controls	Signal Type	Signal Frequency (kHz)	Signal Duration (ms)	Procedure	Method	Environment	Recovery
(Finneran et al., 2015)	Tt	27-29	M	OLY	Water	10 impulses	0.1 s^{-1}	broadband	~0.1–0.5 s	up to 208 (p-p)	Y	FM, AM	0.5, 1, 2, 4, 8, 16, 32, 45, 64	500 ~ 30 s	Staircase Rev/Reg	Behav. AEP	SD Bay	~2–10 min
(Kastelein et al., 2015a)	Pp	7	M	02	Water	2760 Impulses	0.77 s^{-1}	mostly 0.5-0.8	60 min	180 peak	Y	FM	2, 4, 8, 16, 125	1000	Staircase	Behav.	Pool	4, 8, 12, 48 min
(Popov et al., 2015)	Dl	N/A	F	N/A	Water	HOBN	CW	45 (center)	10 min	170	N	pip train	64	~16	Rev	AEP	Shallow pool	1.5-60 min
(Kastelein et al., 2015b)	Pp	8	M	02	Water	FM sweep	CW, 0.1	6–7	1-s sweep, 200 to 2000 s total duration	166	Y	FM	9.2	1000	Staircase	Behav.	Pool	4, 8, 12, 48, 96, 144, 288 min, 24 h

Study	Subjects				Exposure								Hearing Test					
	Sp	Age	Sex	Name	Medium	Type	DC	Frequency (kHz)	Duration	SPL (dB)	Controls	Signal Type	Signal Frequency (kHz)	Signal Duration (ms)	Procedure	Method	Environment	Recovery
(Reichmuth et al., 2016)	Pl	3	M	Tunu	Water	Single impulse	Impulse	broadband	~0.1 s	191-206 p-p	Y	FM	0.1	500	Staircase	Behav.	Pool	24 h
(Reichmuth et al., 2016)	Pl	3	M	Amak	Water	Single impulse	Impulse	broadband	~0.1 s	190-205 p-p	Y	FM	0.1	500	Staircase	Behav.	Pool	24 h
(Reichmuth et al., 2016)	Ph	16	M	Natchek	Water	Single impulse	Impulse	broadband	~0.1 s	191-206 p-p	Y	FM	0.1	500	Staircase	Behav.	Pool	24 h
(Reichmuth et al., 2016)	Ph	2	F	Nayak	Water	Single impulse	Impulse	broadband	~0.1 s	190-206 p-p	Y	FM	0.1	500	Staircase	Behav.	Pool	24 h
(Kastelein et al., 2016)	Pp	9	M	02	Water	Multiple impulses	0.77 s^{-1}	mostly 0.5-0.8	15-360 min	144	Y	FM	8	1000	Staircase	Behav.	Pool	4, 8, 12, 48 min
(Kastelein et al., 2016)	Pp	3	M	04	Water	Multiple impulses	0.77 s^{-1}	mostly 0.5-0.8	15-360 min	144	Y	FM	8	1000	Staircase	Behav.	Pool	12, 16, 24, 60
(Kastelein et al., 2017a)	Pp	6	F	05	Water	Narrowband sonar	96%	3.5–4.1	30, 60 min	142	Y	FM	4, 5.7	1000	Staircase	Behav.	Pool	4, 8, 12

Study	Subjects				Exposure								Hearing Test					
	Sp	Age	Sex	Name	Medium	Type	DC	Frequency (kHz)	Duration	SPL (dB)	Controls	Signal Type	Signal Frequency (kHz)	Signal Duration (ms)	Procedure	Method	Environment	Recovery
(Kastelein et al., 2017a)	Pp	3	M	06	Water	Narrowband sonar	96%	3.5–4.1	30, 60 min	142	Y	FM	4, 5.7	1000	Staircase	Behav.	Pool	4, 8, 12
(Kastelein et al., 2017b)	Pp	3	M	06	Water	Multiple airgun impulses	12–27 s interval	Broadband (< 1 kHz)	10 or 20 shots	194, 199 peak	Y	FM	0.125, 0.25, 0.5, 1, 2, 4, 8, 16, 32, 64, 125	1000	Staircase	Behav.	Pool	4, 8, 12
(Popov et al., 2017)	Dl	3	F	N/A	Water	HOBN	CW	32	10 min	170	N	pip train	45	~16	Reg	AEP	Shallow pool	5,15, 25, 50 min
(Kastelein et al., 2018)	Pv	7-9	F	02	Water	Multiple impulses	0.77 s^{-1}	mostly 0.5-0.8	180, 360 min	~176 peak	Y	FM	4, 8	1000	Rev	Behav.	Pool	4, 8, 12, 60 min
(Kastelein et al., 2018)	Pv	7-9	F	01	Water	Multiple impulses	0.77 s^{-1}	mostly 0.5-0.8	180, 360 min	~176 peak	Y	FM	4, 8	1000	Rev	Behav.	Pool	16, 20, 24, 72 min

Study	Subjects				Exposure								Hearing Test					
	Sp	Age	Sex	Name	Medium	Type	DC	Frequency (kHz)	Duration	SPL (dB)	Controls	Signal Type	Signal Frequency (kHz)	Signal Duration (ms)	Procedure	Method	Environment	Recovery
(Kastelein et al., 2019b)	Pv	12	F	F01	Water	SOBN	CW	16 (center)	60 min	128-149	Y	FM	16, 22.4	1000	Staircase	Behav	Pool	12-16, 16-20, 20-24 min
(Kastelein et al., 2019b)	Pv	12	F	F02	Water	SOBN	CW	16 (center)	60 min	128-149	Y	FM	16, 22.4	1000	Staircase	Behav	Pool	1-4, 4-8, 8-12, 60, 120 min
(Kastelein et al., 2019a)	Pv	8-10	F	F01	Water	Tone	CW	6.5	60 min	123-159	Y	FM	6.5, 9.2, 13	1000	Staircase	Behav	Pool	12-16, 16-20, 20-24, 72, 132, 252, 1200 min
(Kastelein et al., 2019a)	Pv	8-10	F	F02	Water	Tone	CW	6.5	60 min	123-159	Y	FM	6.5, 9.2, 13	1000	Staircase	Behav	Pool	1-4, 4-8, 8-12, 60, 120, 1440 min

Study	Subjects				Exposure								Hearing Test					
	Sp	Age	Sex	Name	Medium	Type	DC	Frequency (kHz)	Duration	SPL (dB)	Controls	Signal Type	Signal Frequency (kHz)	Signal Duration (ms)	Procedure	Method	Environment	Recovery
(Kastelein et al., 2020a)	Pv	11	F	F01	Water	SOBN	CW	32 (center)	60 min	92-152	Y	FM	32, 45, 63	1000	Staircase	Behav	Pool	12-16, 16-20, 20-24, 72, 132, 252 min; 24, 48, 72 h
(Kastelein et al., 2020a)	Pv	11	F	F02	Water	SOBN	CW	32 (center)	60 min	92-155	Y	FM	32, 45, 63	1000	Staircase	Behav	Pool	1-4, 4-8, 8-12, 60, 120, 240 min; 24, 48, 72, 96 h
(Kastelein et al., 2020b)	Pv	12	F	F01	Water	SOBN	CW	40 (center)	60 min	126-153	Y	FM	40, 50, 63	1000	Staircase	Behav	Pool	12-16, 16-20, 20-24, 72,

Study	Subjects				Exposure								Hearing Test					
	Sp	Age	Sex	Name	Medium	Type	DC	Frequency (kHz)	Duration	SPL (dB)	Controls	Signal Type	Signal Frequency (kHz)	Signal Duration (ms)	Procedure	Method	Environment	Recovery
																		132, 252 min; 24, 48, 72 h
(Kastelein et al., 2020b)	Pv	12	F	F02	Water	SOBN	CW	40 (center)	60 min	126-153	Y	FM	40, 50, 63	1000	Staircase	Behav	Pool	1-4, 4-8, 8-12, 60, 120, 240 min; 24, 48, 72, 96 h
(Kastelein et al., 2020c)	Pp	4	M	M06	Water	Multiple Airgun Impulses (single airgun)	$0.25\ s^{-1}$	Broadband (< 1 kHz)	1350 shots (~87 ms/shot)	194 dB pk		FM	2, 4, 8	1000	Staircase	Behav	Pool	1-4 min
(Kastelein et al., 2020c)	Pp	4	M	M0	Water	Multiple Airgun Impulses	Every 13-18 s	broadband	10 or 40 (~87	202 dB pk		FM	2, 4, 8	1000	Staircase	Behav	Pool	1-4, 4-8 min

Study	Subjects				Exposure								Hearing Test					
	Sp	Age	Sex	Name	Medium	Type	DC	Frequency (kHz)	Duration	SPL (dB)	Controls	Signal Type	Signal Frequency (kHz)	Signal Duration (ms)	Procedure	Method	Environment	Recovery
						(single airgun)			ms/shot)									

E Annex 5 - Marine mammal monitoring and operational measures for mitigating noise from geophysical surveys and vessels: a review with emphasis on Antarctic waters

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E.1 Introduction

The Protocol on Environmental Protection of the Antarctic Treaty (the 'Protocol') stipulates that all activities in the Antarctic Treaty area (south of 60°S) shall be planned and conducted so as to limit adverse impacts on the Antarctic environment and dependent and associated ecosystems. Underwater noise has been identified as a major stressor in the marine environment, and can have a profound effect on marine organisms, particularly marine mammals (e.g. Richardson 1995, Southall et al. 2007, Erbe et al. 2019b). Many anthropogenic activities in the Antarctic generate underwater noise, ranging from ship traffic to construction and scientific seismic surveys, yet no specific guidelines for noise production in the Antarctic have been established (Erbe et al. 2019a).

In November 2018, in an expert workshop hosted by the German Environment Agency (Umweltbundesamt, 'UBA') in Berlin, expert stakeholders identified key research and management needs relating to the effects of noise on Antarctic marine mammals (reported in Erbe et al. 2019a). One of the top-ranking research needs was an assessment of the effectiveness of various noise mitigation options. One of the conclusions of the workshop in 2018 was to recommend a series of focused international expert workshops to develop exposure limits for behavioural impact and auditory injury for Antarctic marine mammals, along with a workshop to discuss noise mitigation options. The aim of this mitigation workshop will be to identify the benefits and limitations of existing mitigation measures, and to understand which of these measures are most suitable in a given situation and for a given species of interest.

These recommended workshops are now the focus of an UBA-financed project[23], initiated in 2020, which includes several short desk-based studies to be prepared in advance of the workshops. The current study provides background information to inform the workshop on mitigation options.

This section focuses on noise sources of relevance to UBA in their role as regulator of German activities in the Antarctic, which concern the operations of the Alfred Wegener Institute's ice-breaker polar research vessel, RV *Polarstern*. These include: seismic survey using airguns, the use of high-resolution geophysical (HRGS) equipment including multi-beam echo-sounder (MBES) and parametric sub-bottom profiler (SBP), and the noise of the vessel itself (Schuster 2021). For brevity, we collectively refer to seismic (i.e., airguns) and HRG survey as 'geophysical' survey hereafter. The scope of these sources and activities is of relevance to any vessel conducting geophysical survey in shelf to deep-ocean environments. For example, multiple nations operate research vessels which undertake geophysical surveys in Antarctic waters for the purposes of studying seabed habitats, plate tectonics or palaeoceanographic and climate history (Boebel et al. 2009, Breitzke 2013).

There are multiple approaches to mitigating the effects of geophysical surveys and vessel noise, which can be implemented at different stages. Gordon (2018) summarises these as:

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[23] "Detrimental effects of underwater noise - Development of the basics for a noise protection concept for Antarctica."

- The pre-planning stage (e.g., collecting baseline data on species occurrence and spatio-temporal variability);
- The planning stage (e.g., adapting the sound source, reducing exposure through survey timing and design); and,
- The post-planning stage, including:
- Medium-range detection and risk reduction techniques (e.g., pre-activity survey at a scale of days to weeks prior to a survey for identification and potential avoidance of areas of higher density); and,
- Real-time detection and risk reduction during the operational phase (e.g., mitigation zone monitoring and shut-down procedures).

It is acknowledged that some of these approaches, in particular pre-planning and pre-activity baseline surveys, are less feasible in Antarctic waters due to the inaccessibility of the region and resource constraints within specific cruises, although the use of habitat mapping approaches may be informative at a planning stage (Bombosch et al. 2014).

Operational phase mitigation is generally designed to minimise the probability of animals being exposed to sounds levels which may cause hearing damage such as reducing the power of or shutting down the acoustic source when animals are observed entering, or about to enter, a ‘mitigation zone’ around the noise source. Detecting an animal in time to implement mitigation measures before it enters a mitigation zone is therefore important to consider, with a high detection probability being vital (Verfuss et al. 2016, 2018). **Therefore, using monitoring methods to quickly and reliably detect and localise marine mammals is essential. It is this operational stage, comprising real-time monitoring for detection and mitigation, which is the focus of the current study.**

In summary, this study provides a high-level review of real-time monitoring options for marine mammal detection and operational measures for noise mitigation in order to minimise the effects of noise from geophysical surveys and vessels on marine mammals, with a specific focus on Antarctic waters.

Specific objectives include:

- A **review** listing and summarising relevant detection approaches and mitigation measures that can be applied, including their suitability to different species and circumstances,
- **Targeted interviews** to gather information on practical experiences of different approaches to detection and mitigation, including challenges and potential solutions. Where possible, identify those of particular relevance to Antarctic waters and species.
- **Identification of example procedures** for marine mammal detection and noise mitigation implemented by a selection of users of Antarctic waters.

It is intended that this review will provide a starting point for discussions at the forthcoming mitigation workshop.

E.2 Approach

E.2.1 Literature review

Three highly relevant resources already exist which are useful for the scope of this chapter:

- A comprehensive assessment of currently available and near-future real-time monitoring techniques for marine mammals in low-visibility conditions, with a focus on techniques suitable for application to seismic survey (Verfuss et al. 2016, Verfuss et al. 2018);
- A review of unmanned vehicles for the detection and monitoring of marine fauna (Verfuss et al. 2015, Verfuss et al. 2019); and,
- A review of mitigation measures to reduce the risks to marine mammals from acoustic exposure, including some specific consideration of Antarctic species and conditions (Gordon 2018).

While the scope and/or level of detail of the aforementioned reviews is greater than that of the current study, there is considerable overlap. To avoid excessive repetition of these existing studies, and maximise the potential for added value, the current study focuses on practical challenges and potential solutions associated with those operational mitigation measures of greatest relevance to geophysical surveys in Antarctic waters. Furthermore, emphasis is placed on technological developments and subsequently published literature.

It is also acknowledged that synergies exist between the current study and another component short study to the wider UBA project: *Review of anthropogenic underwater noise sources commonly used for research in Antarctica* (Schuster 2021), which lists potential mitigation options for reducing ship noise and geophysical survey equipment at the source. Reference is made to this review where appropriate.

E.2.2 Targeted interviews

Persons with experience relevant to the project were contacted by email to provide an overview of the project and to invite them to participate in an informal interview. The selection of potential interviewees drew upon:

a) selected participants from the 2018 Berlin workshop;

b) relevant past collaborators of the project team, for example, those involved in a review of monitoring approaches for low-visibility conditions (Verfuss et al. 2018);

c) identification of additional relevant persons through background research; and,

d) recommendations gathered through the current UBA project team and the interviews themselves.

A total of twelve people were interviewed. The experience and background of interviewees included marine mammal and geophysical research in Antarctic waters, mitigation programme and policy development, research and development of monitoring tools (academia and industry), and practical implementation of mitigation in a Marine Mammal Observer (MMO) / Passive Acoustic Monitoring (PAM) operator role. Names of interviewees and further details of their relevant experience are provided in Appendix 1 to Annex 5 - Interviewee list and relevant experience. While some affiliations are listed, all interviewees participated as individuals rather than representatives of an institution or organisation.

Indicative questions (Figure E. 1) were provided at least one week prior to interview to allow participants time to prepare. Each interview comprised a video call of approximately one-hour duration and followed an informal / semi-structured approach to cover the questions sent in advance but allow flexibility to suit the expertise of the specific interviewee. Interviews were not recorded but dialogue was captured in typed notes.

Figure E. 1: Indicative questions provided to interviewees.

1. **What regions have you worked in, and under which associated mitigation regulations/ guidelines?**
2. **What different approaches to monitoring have you used for marine mammals, and for mitigation in relation to geophysical survey? (e.g., visual observations, assisted visual observations (infrared etc), towed PAM, static PAM)**
3. **For each of these approaches,**
    - **In what circumstances have you found them to be the most/least effective? (e.g., how did this vary by species, regions, conditions?)**
    - **What practical challenges have you faced?**
    - **How did you attempt to overcome these challenges, and was this effective?**

Source: Author’s own.

Relevant interviewees (i.e., those with practical experience in Antarctic waters) were also asked about the specific mitigation procedures (and associated formal guidelines where applicable) which were implemented. The interviews were supplemented by targeted emails to relevant national research programmes and searching of the **US national register of relevant approvals** and **US federal register**[24].

E.2.3 Presentation of results

The information obtained from literature sources and interviews was compiled and is summarised in Section E.3, grouped by the methodological approach.

For each methodological approach, the following is provided:

- Overview of the approach, current state of development and relative suitability for different species and conditions, mainly summarising the three key publications identified in Section E.2.1, supplemented with other literature and information given by the interviewees where appropriate,
- Summary of practical issues and potential solutions, with focus on those of key relevance to Antarctica where applicable,

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[24] https://www.fisheries.noaa.gov/protected-resource-regulations

Details of the relevant input gathered through interviews is presented in Appendix 2 to Annex 5 - Interviewee input related to visual monitoring.

Section E.4 provides example mitigation procedures used in Antarctic waters. Key strengths and limitations of each methodological approach presented in Section E.3 are summarised in Section E.5, along with a summary of specific considerations for Antarctic waters (Section E.6) and recommendations (Section E.7).

E.3 Operational detection and mitigation measures

The current marine mammal monitoring methods used for mitigation purposes are visual monitoring, monitoring with electro-optical imaging sensors (mostly thermal infrared (IR)), and passive acoustic monitoring. Each of these methods has distinct strengths and limitations, and the extent to which they will contribute to effective monitoring will vary according to the circumstances and objectives to which they are applied, including the target species, required detection range and environmental conditions (Verfuss et al. 2018). Each method requires trained personnel in order to achieve a high detection efficiency to minimise the risk of animals being impacted, and a low false alarm rate (i.e., detections that are thought to be marine mammals but are not) to minimise unnecessary mitigation measures. Methods requiring electronic equipment (e.g., thermal IR or PAM) will further benefit from experienced, technically-trained personnel, and from a well-developed automated detection software pre-selecting potential true detections. Managing the number of false negatives (animals present but missed by a detection system) is crucial for the usefulness of any automatic detection system. In a mitigation setup, false negatives are not wanted, as this increases the risk to the animals. However, ensuring that all potential animals are detected with certainty may result in an unmanageable volume of false detections. A balance needs to be struck which minimises the risk of a missed detection with the number of false detections which a system operator can manage. One interviewee noted that a dedicated operator in a dark room (i.e. with few distractions) can process a higher number of false alarms than a non-dedicated crew member who may be working on other tasks simultaneously. A low but constant rate of false detections is desirable, as it can help to keep the operator(s) alert (Zitterbart et al. 2020).

While using a combination of monitoring methods may increase the detection efficiency, the suite of monitoring tools requires considerable resources, including investment in equipment and multiple trained personnel. The level of monitoring and investment into equipment should therefore be chosen proportional to the resulting benefit, considering the expected noise impact of an activity being undertaken and the sensitivity of the area and species present.

In the following paragraphs, the strengths and limitations of each monitoring method is discussed, with focus on their usage from onboard a vessel, but also for other applications (e.g., from unmanned platforms). While detecting animals in or near the mitigation zone usually leads to a delay in the noise-emitting activity or to a shut-down of it, other noise mitigation measures are discussed in the last two sections of this chapter.

E.3.1 Visual monitoring

Visual monitoring, by trained observers using naked eye and binoculars, is the most widely-used method of detecting marine mammals within a zone of interest around the vessel/noise source. During daylight hours and good environmental conditions, it is typically the primary method of real-time detection for mitigation from geophysical survey. Visual monitoring relies on visual cues that can be detected at the surface, such as exhalation blows and body surface breaks. The visibility and frequency of these cues is species-dependent, therefore the effectiveness of visual monitoring is species-specific. For example, short-diving large animals (e.g. baleen whales), or smaller animals which are gregarious and/or highly active at the surface (e.g. delphinids) are more readily detected by visual monitoring compared to smaller and/or more cryptic surfacing species (e.g. porpoises, beaked whales) and those which perform long, deep-dives (e.g. beaked whales, sperm whales). In good conditions and with an elevated viewpoint, reliable detection ranges from visual observations are typically in the hundreds of metres for porpoises, small delphinids and beaked whales, 1 km or more for other medium-sized odontocetes and small mysticetes, and several kilometres for sperm whales and larger mysticetes (review in Leaper et al. 2015). Seals can be particularly difficult visual targets at sea, with reliable detection ranges generally limited to low hundreds of metres. However, seals hauling out on ice are easier to detect and can alert visual observers to potential further seals in the surrounding water (Section E.9, Table E. 6).

In all cases, individual cues are sporadic, ephemeral, and the probability of their detection is dependent on environmental conditions, and the observer's level of vigilance, experience and skill (Verfuss et al. 2016). The experience of the observers has been shown to be important not only in terms of detection rates, but also for distance estimates and species identification (e.g. Barlow et al. 2006, Stone 2015, Smith et al. 2020). Maintaining visual vigilance is mentally and physically taxing; an observer's performance will diminish if they are fatigued or uncomfortable, and will fatigue more quickly in poor sighting conditions.

Visual observations cannot be conducted at night, and are impaired by environmental conditions such as fog, precipitation, high sea states, sun glare or low light (Verfuss et al. 2016). In particular, visual detection becomes increasingly difficult as sea state increases (Palka, 1996), with detection of smaller, more cryptic species such as porpoise much reduced in Beaufort sea state (Bft) > 1.

The effectiveness of visual observations is also reliant upon cues occurring within the field of view of the observer(s), which is influenced by the number of observers (more observers provide greater coverage) and the presence of obstructions such as the ship's flue, radar, communications antennae and cranes (which can limit the field of view). For mitigation purposes it is generally necessary for one or more observers to scan 360° around the survey vessel, and the observer may simply not be scanning the animal's location at the time when a cue is produced.

As identified through targeted interviews, a key challenge when using visual observations for mitigation is accurate estimation of distance, and therefore animals' location relative to mitigation zones. Distance measuring sticks and reticule binoculars can be subject to considerable error, particularly where the observation platform is not particularly high (see Table E.6). Laser rangefinders can theoretically be used to estimate distance to objects with a high degree of accuracy. With a dedicated operator they have been used successfully in scientific research projects for focal follows of dolphins to several hundred metres range (V. Janik, pers. comm., March 2021). However, they require a large, clear target above water to be 'hit' by the laser, which is rarely to be achieved during the typically brief sightings within a cetacean survey (Gordon 2001, Dawson et al. 2008). For example, trials by Gordon (2001) showed range estimates from laser rangefinders may be returned for objects other than the apparent target. Dawson et al. (2008) points out that range finders seldom receive enough reflected energy to measure distances to sightings, unless for large targets at close range. Interviewees with more recent experience of using laser rangefinders alongside visual monitoring duties reported similar challenges; while they expressed that they could be useful for training observers to estimate distances by eye, they did not find them to provide an effective tool for measuring distances to animals in a vessel-based mitigation monitoring application.

With specific regard to conducting visual observations in Antarctica, multiple interviewees expressed that the biggest challenge relates to the weather, including frequent high sea states, precipitation, and extreme cold. This makes detection of animals challenging and presents logistical challenges in terms of the positioning (inside or outside) of observers, having a sufficient number of observers to be regularly rotated, and potential compromises among the ship's crew to accommodate a sufficient number of observers. More detailed interviewee feedback in relation to visual monitoring is presented in Section E.9, Table E. 6.

E.3.2 Electro-optical imaging sensors (vessel-based)

The past decade or so has seen the development and application of an increasing diversity of sensors that may assist visual observations, particularly during low light conditions. These may be handheld devices, or mounted on a ship, with mounted units requiring a robust stabilisation system (gimbal) to compensate for the ships' movement. While hand-held devices are of limited effectiveness due their limited field of view and small display, the set-up of mounted cameras can be optimised to support or complement visual monitoring (see Table E.6). Such systems require technically trained personnel, but have the advantage that imagery is available for subsequent review of a sighting to confirm details.

There are three main categories of sensors in use in a mitigation monitoring context: thermal infrared (IR), near IR (commonly referred to as light-enhancing or night-vision), and RGB (visible spectrum). The focus here is primarily on thermal IR, and specifically on mounted systems, as these represent the most promising approach to low-visibility detection and include the most developed systems to date.

Thermal IR systems

Thermal IR sensors detect IR radiation emitted by objects rather than reflected light, with the amount of radiation emitted by the object dependent on its temperature. Therefore, they can operate during day or night. When an animal surfaces and reveals part of its warm body or exhalation (blow), the thermal contrast between body or blow and the colder sea surface is detected by the thermal IR sensor. The images from thermal IR cameras can be viewed in real-time and are typically complemented by algorithms for automated detection of potential marine mammals. Mounted systems include a monitoring station within the ship, typically on the bridge, where images are displayed on monitors. When a detection is made, an alert is generated which is typically accompanied by a bearing, range and images/video segment of the detection; alerts and imagery may also be linked to portable computers/tablets. During daylight and good sighting conditions, visual observers may follow-up the alerts to confirm the detection and gather more information such as species ID, group size and heading. At night, when the thermal IR system provides the primary method for animal detection, the system is typically monitored by one or more dedicated observers.

Thermal IR can be a useful tool supporting visual observers during times of high visibility and thereby increase detection rates. It can be used as a mitigation tool at night, where visual observations are not possible, and in moderate sea states where visual observation become less effective. There are still certain environmental conditions that strongly affect the efficiency of thermal IR, such as fog, precipitation and detection rates fall at sea states > Bft 4. Similar to visual monitoring, it is dependent on cues at / above the sea surface and therefore more suited to short-diving, large animals, and least suited to long-diving elusive animals. The surface-active nature of some smaller cetaceans (e.g. dolphins) provide reasonable cues for thermal IR, although detection distances are less than for large whales.

These camera systems can also be set up to measure range from the angle between the horizon and the detection, providing a key advantage over visual observers, where range estimation is often poor. The placement of thermal IR technology is important for performance, as detection can be inhibited by proximity to floes, and reflection from vessel decks.

The cost of purchasing and installing a thermal IR system range from $20,000 to over $200,000 USD depending on the system and number of units required to provide the necessary coverage (Verfuss et al. 2018). IR detections can currently only be classified into broad marine groups by human observers, leading to the suggestion that the utility of IR is as an alert system for MMOs, rather than a stand-alone detection and classification system (Smith et al., 2020). While classification to species-level might not be necessary in some mitigation applications, there remains a need for a human operator to confirm true detections; the subsequent need for an MMO to further investigate detections through visual observations (where possible) would be an activity- and mitigation plan-specific decision to be made by the relevant regulatory authority.

For a ship-based thermal IR system, waves and birds (and small ice chunks in polar waters) are the most likely source of false alerts (which may also be problematic for visual observers). Breaking waves have been reported to cause a significant number of false alerts (Zitterbart et al. 2013; Smith et al. 2020), but only during higher sea states (i.e. > Bft 4). Seabirds in the air and on the sea surface have also been reported to be a major source of false alerts on ship-based deployments and need more attention in the automatic detection algorithm development (Smith et al. 2020).

Several commercial systems are available and being routinely used for marine mammal detections, ranging from the application of one or more thermal IR cameras with a fixed field of view, to panning directional cameras with a fixed field of view, to a rotating line scanner. In addition to noise mitigation applications, the potential for thermal IR systems as a tool to mitigate vessel collision risk is helping to drive their development (Horton et al. 2017).

Rotating line scanner

The only panning/rotating system with extensive published data on its effectiveness is the Automated Infrared-based Marine Mammal Mitigation System (AIMMMS) developed by Rheinmetall Defence, a rotating line scanner and custom data acquisition and processing software (Tashtego) supporting automatic detection and distance/bearing measurements. This system, and earlier iterations, has been deployed from several different survey vessels (Weissenberger and Zitterbart 2012, Smith et al. 2020) including the RV *Polarstern* in Antarctic waters (Zitterbart et al. 2013, Zitterbart et al. 2015) and land platforms (Zitterbart et al. 2020). This high-specification system scans 360° horizontal x 18° vertical at 5 revolutions per second, providing a 5-Hz video stream of the thermal field of the ship’s surrounding environment. The AIMMMS is the only rotating line scanner we are aware of. Over the years, this system has undergone considerable development and testing as a tool for real-time marine mammal detection and has proven thermal IR as an effective method for above-surface marine mammal monitoring, especially in cold-water locations such as Antarctic waters, and has more recently also shown to be effective in sub-tropical and temperate waters (Zitterbart et al. 2020). It can detect whale blows day and night to several kilometres range, and is also quite robust to the effects of sea state, remaining highly effective to sea state 4. Results show that the use of thermal imaging systems alongside MMOs enhances detection rates and can be a valuable addition to marine mammal monitoring programmes (Smith et al. 2020, Zitterbart et al. 2020).

Panning directional camera systems

There are several panning camera systems with a directional fixed field of view on the market (e.g., Dual Camera System Seiche, Gobi by Xenics, Hyper-Cam by Telops, NightNavigator by Current Scientific Solution etc). A full review of those is given in Verfuss et al. (2018). Here we describe the Seiche Dual Camera System as an example for a panning system (see Section E.9, Table E. 7). The full system includes three panning camera units (port, starboard and either bow or stern) to achieve a 360° view. The thermal IR is supported by RGB video, which can be viewed at a monitoring station within the vessel. Automated detection and distance estimation are possible through the proprietary ARC and RADES software, respectively, and the video images allow for species identification.

Targeted interviews provided positive feedback on thermal IR camera systems; multiple interviewees, including experienced MMOs in addition to those involved in the development of such systems, expressed that mounted systems provided a valuable daylight supplement/night-time alternative to visual observations, particularly for baleen whales. The most widely noted limitation was poor system performance in fog. Detailed interviewee feedback in relation to thermal IR and other camera systems is presented in Table E.7. Their experience related to the AIMMMS and its subsequent configurations; the mounted dual camera system (paired HD RGB and thermal IR) developed by Seiche; and, limited experience with handheld devices.

Other spectral systems

Spectral camera systems other than thermal IR systems can include normal optical cameras that only use visible light (RGB) or may achieve enhanced low-light performance by detecting and amplifying non-visible sources of electromagnetic radiation such as ultraviolet or near-infrared. Light-amplifying technology generally comprises handheld units (commonly referred to as night-vision goggles) and differs to thermal IR in that it relies upon there being some reflected light available to amplify/enhance (such as moon, starlight, or deck lighting) and so cannot operate in total darkness. As such, their effective range and circumstances in which they may be used are limited, and have seen limited development as a marine mammal mitigation tool (MMOA website 2021). Nonetheless, they are often recommended for use in low-light mitigation monitoring in US waters. Several interviewed MMOs commented on night-vision units, indicating mixed experiences depending on the quality of the unit and the ambient light conditions, and noting that they were strongly negatively affected by any moisture in the air.

With regard to RGB camera systems, these have the same restrictions as visual observers as they are only useful for good-visibility conditions (i.e. low sea states, good weather) (Verfuss et al. 2016). Furthermore, there is a trade-off between field of view and resolution, and multiple units are required to provide comprehensive coverage around a vessel. We are not aware that these systems are often used in vessel-based applications, other than in parallel to thermal-IR as done for the Seiche system mentioned in Section E.3.2. RGB and other spectral systems used in normal daylight conditions are more commonly found in combination with aerial systems (Section E.3.3). In the Seiche system, the RGB camera imagery can complement the thermal IR by providing a video record of detections to assist in species ID if this was not possible in real-time by a visual observer, and an image overlay of mitigation zones may assist in determining distance and decisions on mitigation action to take.

E.3.3 Passive acoustic monitoring

Passive acoustic monitoring (PAM) facilitates the detection of vocal marine mammals during subsurface activity. Different configurations of hydrophones combined are used to detect and localise animals through vocal cues used for orientation, to locate and capture prey, mate selection and social interactions. Hydrophones are monitored aurally by human observers and using acoustic analysis software, such as the open source PAMGuard software (Gillespie et al. 2008), to detect, classify and localise marine mammal vocalisations in real-time (Verfuss et al. 2018). The use of PAM is routinely encouraged and/or a requirement in mitigation guidelines for geophysical survey as a complement to visual monitoring. This is particularly true where activities are planned to be undertaken at night, when visual sighting conditions are poor, in particularly sensitive areas, or areas with species for which visual observations are less effective (e.g. deep-diving odontocetes) (Compton et al. 2008, Verfuss et al. 2016, Gordon 2018).

Detailed interviewees comments with regard to PAM are given in Section E.9, Table E. 8.

Towed PAM

For monitoring during geophysical surveys, PAM is implemented through a towed array of hydrophones, most commonly as an ancillary cable system of 100-400 m length deployed alongside the seismic source array, or rarely from some other vessel nearby (e.g. guard vessel). In recent years, integrated towed PAM systems have been developed which integrate the hydrophones into the streamers of the seismic source (e.g. Sercel's 'QuietSea' system).

The extent to which PAM is useful for detecting marine mammals for real-time monitoring for mitigation purposes varies considerably between species and with applications, being influenced in particular by the equipment used, the vocal behaviour of particular species (which may vary by season, location and gender), how these sounds propagate in the environment, and the total noise field within which detections must be made. It works well with most odontocete species, although the detection range for species which vocalise at very high frequencies (e.g. porpoise) may be too short to cover the typical size of mitigation monitoring zones.

Key strengths of PAM are that it does not rely on animals breaking the sea surface, and therefore can be more effective than visual or imaging systems (e.g. thermal IR) at detecting frequently vocalising species which spend prolonged periods underwater, such as deep diving odontocetes. In contrast to visual observations, PAM is not at all affected by fog or low/no light, and is also less negatively affected by precipitation or high sea states, although its effectiveness may be somewhat reduced by elevated background noise during high seas states or rainfall (Verfuss et al. 2016, Smith et al. 2020).

A key challenge in the implementation of towed PAM for mitigation monitoring is vessel noise masking biological sounds, especially the low-frequency vocalisations of some baleen whales such as fin and blue whales (JNCC 2017, Gordon 2018). This issue was widely acknowledged by interviewees; several noted that sinking the hydrophone array and maximising the distance between the vessel and the hydrophones would reduce the influence of vessel noise, but that the probability of detecting low-frequency vocalisations remained low. The low vocalisation rates of many baleen whales is an additional limiting factor in the extent to which PAM may be useful for real-time mitigation of this species group (Verfuss et al. 2016).

The increased number of hydrophones and the distance between hydrophones and the vessel enabled by integrated towed PAM arrays may further mitigate the effects of vessel noise masking and reduce the logistical complexity and entanglement risk associated with ancillary arrays. These systems are still in development and little has been published on the performance of the two currently available commercial systems ('QuietSea' and 'WhaleWatcher'), although it is noted that QuietSea now offers a wide frequency bandwidth of 180 kHz (enabling detection of very high-frequency cetaceans) and has been **authorised for use by the UK regulator**. An alternative to deploying towed PAM from the source vessel, which might reduce vessel noise, would be to deploy from an alternative platform, such as a quieter guard vessel or an autonomous vehicle, which could be positioned in advance of the source vessel.

Another key challenge for real-time mitigation is a limited ability for PAM arrays to provide a location for the detection in a sufficiently timely manner, while there can also be considerable uncertainty in the error surrounding localisation estimates (noted by several interviewees). Animals with low vocalisation rates will be particularly difficult to localise as multiple bearings are required to estimate the individual's location. More complex arrays would improve real time detections and localisation, however further development and implementation of hydrophone survey technology would be required (Gordon 2018).

Further considerations voiced by interviewees included a lack of calibration of hydrophones and information on their sensitivity and detection range in commercial applications; this information is critical to understanding if the array is suited to the species of interest. The experience of PAM operators was also raised as a key issue. For ancillary arrays, the risk of entanglement with the source array requires careful consideration.

With regard to implementation of towed PAM in Antarctic waters, such methods cannot be relied upon for reliable real-time detection of baleen whales or seals, and may offer an insufficient detection range for spectacled porpoise; however, towed PAM can provide a useful tool for many odontocete species, particularly in areas where deep-divers such as sperm and beaked whales may occur. Masking from vessel noise is understood to be a key issue for some polar vessels, such as RV *Polarstern* (see Schuster 2021), which may limit the effectiveness of towed PAM for all species groups. Deploying a towed PAM array from a second manned vessel is unlikely to be an option in Antarctica or other remote areas where only a single vessel is used. The presence of sea ice may add logistical complexity and risk to deployment of ancillary PAM arrays and also the use of unmanned platforms for deployment.

Static PAM

PAM integrated within static (i.e. moored surface buoys) and drifting systems have the potential to provide real-time data through WiFi, radio or satellite link. However, they are considered to have limited utility for real-time monitoring for a (moving) geophysical survey vessel (Verfuss et al. 2016). To provide benefit in such an application, they would need to be deployed in advance of a survey commencing and be able to transmit data to the source vessel in real-time or near-real-time. If deployed in an array across the survey area, detections could inform the source vessel of the occurrence of marine mammals within certain areas and the survey route be adapted to avoid areas of recent occurrence, reducing the potential for interaction and shutdown.

To our knowledge, examples of such applications are lacking, although one interviewee noted an application to dredge spoil dumping, where near-real-time detections from two PAM buoys allowed the vessel to avoid dumping dredge spoil at the location where animals were recently detected. Interviewees highlighted the benefits of static PAM over towed in terms of much lower potential for vessel noise masking, particularly for baleen whales, and the potential for long-distance propagation of low-frequency sounds in the surface duct within Antarctic waters (see Schuster 2021).

Separate unmanned platforms

Unmanned vehicles can provide a separate platform for the detection of marine mammals, potentially overcoming some of the limitations of monitoring from the vessel from which noise is generated. They can be deployed in air (Unmanned Aerial Systems – UAS) with optical sensors, or at the sea surface (Autonomous Surface Vehicles – ASV) or in the water column

(Autonomous Underwater Vehicles – AUV) and equipped with PAM. Unmanned vehicles are rarely used for mitigation monitoring, but may be suitable to complement current mitigation methods as described in the previous sections, or overcome some of their limitations (Verfuss et al. 2019). In order to support mitigation monitoring, the systems need to allow for real-time or near-real-time monitoring to enable reacting to the presence of animals; this requires either the transmission of raw data to a competent human operator, or real time on-board processing and the transmission of summary detection data to be checked by a human operator. Where the detection ranges of single unmanned platforms are insufficient to monitor the required area of mitigation, it may be necessary to deploy multiple platforms.

Detailed interviewees comments are given in Section E.9, Table E. 9.

Underwater and surface vehicles

AUVs and ASVs provide platforms onto which PAM systems may be integrated for marine mammal detection, with data subsequently transmitted to an operator (on a vessel or shore) when the platform is able to do so. While the platform will still generate some noise, a key advantage of deploying PAM from AUVs and ASVs is the lack of vessel noise / masking associated with deployment from the survey vessel itself, and therefore the potential for improved detection of acoustic cues, particularly baleen whales whose low-frequency vocalisations are severely masked by vessel noise. Autonomous PAM systems are limited by what can be powered and physically accommodated on the autonomous platform; to date, they have typically used only one or a small number of hydrophones close together, which limits their ability to localise detections (Verfuss et al. 2019). While the larger powered surface vehicles would be capable of towing larger hydrophone arrays, which might provide location data, this is impractical with small low-powered vehicles, since the drag of a large array would overly impact vehicle performance.

Due to the need for a satellite or WiFi data link, AUVs need to surface to transmit PAM data and therefore are not suitable for real-time monitoring for the purposes of detecting animals in relation to a mitigation/shutdown zone (Verfuss et al. 2019). However, both powered and self-powered AUVs (e.g. gliders) equipped with PAM systems may be able to provide near real-time detections of vocalising marine mammals to help guide vessel activities at a broader spatio-temporal scale (Kowarski et al. 2020). For example, a recent study used a buoyancy-driven glider to detect baleen whales in the Gulf of St Lawrence, with a time-lag of between 15 min and 3 h 15 min between an acoustic signal being recorded and data being transmitted to a shore-based human analyst, depending on when the signal occurred within the glider's dive cycle, the weather conditions, and the reporting schedule programmed into the glider (Kowarski et al. 2020).

By contrast, ASVs with PAM systems can readily provide continuous real-time surveillance via wireless connections. While it might not be safe to operate an ASV off the stern of a vessel in close proximity to a noise source such as an airgun array, a potential useful application would be for an ASV to be piloted ahead of the survey vessel to monitor for marine mammals in the vessel's path to provide an early warning of animals potentially entering the mitigation zone. It is not anticipated that such a deployment would be able to cover the monitoring zone, but could complement visual monitoring and/or thermal IR systems (Verfuss et al. 2016).

One interviewee with experience of ASVs discussed PAM applications and the potential for their use as a mitigation tool. While self-powered ASVs (e.g. AutoNaut) could be set up for real-time monitoring, and have the advantage of very low self-noise and long-endurance, their low speed of no more than 3 knots precludes their use for real-time monitoring in relation to a moving vessel noise source (average 5 knots for a seismic vessel); powered ASVs would be more appropriate for such an application, with small-medium ASVs being typically capable of an endurance of multiple days at speeds between 3 and 10 knots (Verfuss et al. 2019). Another interviewee noted the potential safety issues associated with deployment and retrieval of autonomous vehicles from a survey vessel when operating an airgun array, both in terms of entanglement risk and the limited manoeuvrability of the vessel; it would be necessary to deploy the autonomous platform prior to the airgun array, and retrieve following array retrieval. This is a similar perspective to that presented in Verfuss et al. (2015) that AUVs and ASVs would require a reliable navigation system, and may not be considered suitable for mitigation monitoring in operationally busy areas i.e. where multiple vessels were present.

With specific regard to Antarctic waters, there is typically only a single vessel present, and therefore unmanned platforms with PAM systems would not be operating in an operationally busy area in terms of vessel presence. However, the presence of ice may represent a greater risk to the safe operation of the ASV/AUV, and an ASV would not be suitable for deployment in advance of a vessel when operating in sea ice. Any such platforms would need to be 'ruggedised' to operate in the cold temperatures, rough sea conditions and potential presence of sea ice.

Aerial vehicles

Over the past decade there has been a proliferation in the use of unmanned aerial systems (UAS) for wildlife research, including marine mammals (Fiori et al. 2017). While these have not, to our knowledge, been used in a real-time mitigation monitoring application to date, they have the potential to be used concurrently with manned platforms to further increase the probability of animal detection; for example, using UAS with thermal IR cameras in addition to human observers (Verfuss et al. 2019). They could include powered UAS, kites, lighter-than air UAS (i.e. helium blimp), but need to be able to start and land on the main or satellite vessel; as such, systems are likely to be restricted to either those tethered to the vessel, or those capable of vertical take-off and landing (VTOL). Sensors could include thermal IR, RGB or other spectral sensors, with real-time imagery monitoring continuously by a human observer or include the use of automated detection algorithms.

In all such systems, there will be a trade-off between the size of area that can be monitored and the resolution of imagery collected, and there may be a need for multiple UAS to comprehensively cover mitigations zones. Alternatively, an early-warning approach in advance of the survey vessel may be pursued, similar to that described for ASV. The endurance of powered UAS will be a key consideration, with most VTOL systems limited to a maximum of 20-30 minutes of operation before batteries require replacing therefore, they may be more suited to pre-shooting searches than continuous monitoring.

It is important to note that the implementation of any UAS system as part of a mitigation monitoring procedure will require additional expertise and likely additional personnel to those already required for visual observations, particularly for UAS which require piloting.

With specific regard to Antarctic waters, challenges associated with using UAS systems for mitigation are likely to include the influence of cold temperatures and potentially poor weather conditions; these may reduce battery performance of powered systems and subsequent endurance, and present logistical challenges for safe operation. All sensor configurations would be of limited effectiveness in conditions of fog or precipitation. As was done for ship-mounted thermal IR systems (e.g. Zitterbart et al. 2013), any new application of UAS as a real-time mitigation monitoring tool would require extensive development and testing.

E.3.4 Noise reduction

Vessel noise

Underwater noise from vessels can result from propeller cavitation and structure-borne and airborne noise of various machinery (e.g., main engine, generator, pumps and other machinery) (Schuster 2021). Reducing noise associated with integrated hydroacoustic sources (e.g., hull-mounted echosounder) is considered in Geophysical survey sources.

The strongest noise source is typically propeller cavitation, which generally increases with vessel speed, size, and load (Erbe et al. 2019b). IMO (2014) guidelines for the reduction of underwater noise from commercial shipping note that the best opportunities for reduction of underwater noise occur during the initial design of the ship, where detailed consideration of the propellers and hull design can contribute to reduced cavitation noise, and the use of vibration-reduction measures when installing machinery may also result in noise reduction. Modern vessels designed to reduce noise emissions, such as those built to meet ICES CRR 209 or the SILENT class notations for research purposes (see Eurofleets 2014), can result in substantially lower radiated sound levels across a wide frequency band (Schuster 2021). One such example is the Antarctic research vessel RV Investigator (Australia), built to SILENT-R class specification.

For existing ships, it is unlikely to be practical to meet the underwater noise performance achievable by new designs, although some measures can be taken to reduce radiated noise, such as design and installation of new state-of-the-art propellers and installation of wake conditioning devices (IMO 2014). At an operational scale, several studies have shown that reducing the speed of large commercial ships can result in large reductions in radiated underwater noise (Leaper et al. 2014, Joy et al. 2019), with a recent assessment estimating that a 10% reduction in vessel speed could reduce the total sound energy from shipping by around 40% (Leaper 2019). However, the underwater sound field radiated by vessels is complex, and data for RV *Polarstern* indicate that the highest source levels are generated at a slow speed of 6 knots due to heavy cavitation of the propellers at reduced pitch (Schuster 2021). Indeed, for ships equipped with controllable pitch propellers, such as the RV *Polarstern*, there may be no reduction in noise with reduced speed and, therefore, consideration should be given to optimum combinations of shaft speed and propeller pitch (IMO 2014). This highlights the importance of ship-specific knowledge of radiated sound fields when considering operation measures for noise reduction such as reducing vessel speed or modifications to onboard machinery.

At a more strategic operational scale, SCAR (2021) note that changes in shipping routes can limit sound exposure in sensitive areas, and that the IMO Polar Code specifically requires marine mammal distributions to be taken into account in voyage planning.

In summary, the most feasible option for reducing underwater radiated vessel noise is likely to be identification of critical speeds of an individual ship with respect to cavitation, and avoidance of such speeds as far as is possible within the wider safety, operation and energy efficiency requirements of the vessel (IMO 2014).

Geophysical survey sources

Efforts to mitigate noise effects by reducing the sound generated by geophysical sources lie somewhere between operation and planning approaches to mitigation. For example, the use of an alternative seismic source such as marine vibroseis (Duncan et al. 2017, Matthews et al. 2021) or airguns designed to reduce the high-frequency component of generated sound (e.g. Teledyne eSource[25]) would need to be considered at the planning phase and are not discussed

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[25] https://www.teledynemarine.com/en-us/products/Pages/eSource.aspx

here. However, it is noted that one reviewer raised these as potential mitigation, pointing to a recent modelling study of marine vibroseis (Matthews et al. 2021). Another interviewee noted the untested nature of marine vibroseis, and that due to the remoteness and often challenging conditions, Antarctic waters were not an ideal testing ground for new equipment.

At an operational level, there is scope for reducing the potential for noise effects through configuration of the noise source equipment. Examples include configuring an airgun array to minimise horizontal noise radiation, reducing pressure or pulse frequency, and for other equipment reducing pulse lengths, repetition rates, the number of transmitted beams or power (Schuster 2021). All configurations have implications for data quality and it will be necessary to strike a balance between reducing impact and achieving the survey objectives.

E.3.5 Induced avoidance: soft-start

A soft-start (or 'ramp-up') procedure for geophysical surveys is commonly used in an attempt to reduce the risk of potentially permanent auditory damage for marine mammals. Gradually initiating seismic activity at lower sound pressure levels, and 'ramping-up' the acoustic energy is hoped to initiate avoidance behaviour in marine mammals early on in the exposure, and displace them from the surrounding area in order to reduce the likelihood of exposure to noise levels that could cause PTS. However, there is little information on how animals move during soft-starts. Controlled exposure experiments on humpback whales have shown modest avoidance to airgun and sonar ramp-up (Dunlop et al. 2016, Wensveen et al. 2017), while an analysis of several decades of MMO data from seismic surveys in UK waters provided evidence that several species/species groups showed avoidance responses to soft-start procedures (Stone et al. 2017).

The use of a soft-start extends the time that noise is being emitted into the marine environment, which increases the cumulative acoustic energy introduced to the marine environment and may increase impact from exposure at lower noise levels, such as behavioural effects and masking (Gordon 2018). Gordon (2018) suggested that an energy-based soft start, using higher energy levels (within thresholds of instantaneous injury) but a lower pulse rate than typical soft-start procedures could maximise the likelihood of initiating avoidance behaviour in marine mammals while limiting the accumulation of acoustic energy at the animals' ear.

Soft-starts provide a logistically simple option for mitigating against the short-range impacts of geophysical surveys; however, more information is required on the response of individuals, and the most effective method of implementation to deter animals from the critical zone, without causing more disturbance than is necessary (Gordon 2018). For example, one interviewee noted soft-starts are typically not implemented with a doubling of the volume of airguns at each stage, as is recommended in industry guidelines (IOGP 2017), and that the more gradual increase of sound which is typically adopted (e.g. adding one airgun/pair of airguns at a time) may be less likely to cause the desired avoidance behaviour.

Detailed interviewees comments are given in Section E.9, Table E. 10.

E.4 Example mitigation procedures used in Antarctic waters

There is no global standard regarding operational mitigation measures for geophysical surveys, and no guidelines specific to Antarctic Treaty waters. Signatories to the Convention on Migratory Species (CMS) would be obliged to consider the **CMS Family Guidelines on Environmental**

Impact Assessments for Marine Noise-generating Activities[26] ; these include EIA Guidelines for Seismic Surveys (Air Gun and Alternative Technologies) that specify detail for mitigation and monitoring plans, including impact mitigation proposals, but are non-prescriptive in terms of specific mitigation zones, soft-start or shut-down procedures etc.

Multiple countries have developed standard practices for domestic waters (e.g. DoC 2013, JNCC 2017, IBAMA 2018); while there are common themes among these, such as specifying soft-start procedures, other elements can vary considerably resulting in different degrees of precaution (e.g. Castellote 2007). A critique of these national guidelines (e.g. Compton et al. 2008, Parsons et al. 2009, Wright and Cosentino 2015) is beyond the scope of the current study, although it is noted that evidence of their effectiveness, particularly with regard to quantifiable achievement of explicit conservation/protection goals, is largely lacking (SCAR 2021). One interviewee with experience in designing and implementing mitigation plans in multiple regions strongly emphasised the importance of tailoring procedures to specific regions and species of interest; for example, species-specific mitigation zones and power-down/shut-down procedures, informed by noise modelling. By contrast, universal adoption of standard industry/national guidelines could be overly precautious and result in an unnecessarily long and interrupted survey.

It is commonplace for nations undertaking geophysical surveys in Antarctic waters to adopt their domestic guidelines, sometimes with certain adaptations. This is illustrated by examples of mitigation procedures adopted by selected countries/ voyages summarised below. For example, over approximately the last decade the UK's British Antarctic Survey (a component of the Natural Environment Research Council, NERC) have followed the JNCC guidelines when conducting geophysical surveys (R. Larter, pers. comm., Feb 2021). These were superseded by provisions in the 2018 NERC Marine Environment Interaction Policy, based on the JNCC guidelines (JNCC 2017), which set out the requirements for marine mammal observations during seismic and other acoustic survey activities on NERC ships.

On geophysical surveys undertaken in Antarctic waters by Australian research vessels, the provisions of the Commonwealth Government's EPBC Act Policy Statement 2.1 are followed, as are applicable to waters within Australia's EEZ. These mitigation provisions are factored into the environmental assessment and approval process for activities to take place in Antarctic Treaty waters, and may be tailored to suit the specific survey activities and area of operation. Unlike some mitigation procedures, the EPBC Act Policy Statement 2.1 only applies to baleen whales and larger odontocetes, not seals or smaller odontocetes such as dolphins. A specific example relates to the 2017 research cruise of the RV Investigator to waters off the Totten glacier, which included the use of MBES, SBPs and a small high-resolution airgun array (Armand et al. 2018) . Geophysical survey activities were conducted in daylight hours only, and relied on visual observations by one dedicated MMO assisted by crew members on the bridge and a trained person from the scientific team who frequently moved around the bridge to ensure 360°of observations. The vessel benefits from an unobstructed view from the bridge in all directions, aided by extruding port and starboard wings. The cruise report indicated a total of 10 power-downs (1 km zone) and 16 shut-downs (500 m zone) of seismic survey due to marine mammals (all large whales). The mitigation provisions were not mandatory for MBES use but were followed to the extent that shutdown occurred where tracked whales were considered likely to be moving to beneath the vessel.

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[26] https://www.cms.int/sites/default/files/basic_page_documents/CMSFamilyGuidelines_EIAMarineNoise_ConsultationDraft_English.pdf

In an example of a geophysical survey undertaken in Antarctic waters by the US National Science Foundation, mitigation procedures were stipulated in a permit (Incidental Harassment Authorization) issued by NOAA. These were tailored to the specific activity, including an assessment of the sound source and its potential for effects on marine mammals. Unlike the aforementioned UK and Australian procedures, three dedicated, certified observers were required and constant visual observations were required independent of seismic activity. Use of a night-vision device was specified for low-light observations.

Details of mitigation procedures implemented on the RV *Polarstern* during a 2017 cruise to Antarctic waters are summarised in Table E. 1, Table E. 2, Table E. 3, and Table E. 4. These stipulate the use of a team of visual observers and thermal IR system for continuous 24-hour detection, and species-group- and noise source-specific mitigation zones. With regard to practical implementation of these procedures, two interviewees noted the challenges created by seals, which regularly came close enough to trigger shutdown. Seal distribution (particularly crabeater seals) was patchy: few in some areas, then abundant in others, forcing shutdown for hours. It was noted that, to some extent, the likelihood of a shutdown could be reduced by reducing the number of airguns operating (and so reduce the size of the mitigation zone) when animals were detected ahead of the vessel.

Table E. 1: Examples of mitigation procedures adopted by UK geophysical surveys in Antarctica.

Parameter	Seismic survey	Sub-seabed surveys (sub-bottom profiler)	Parameter
Document specifying mitigation measures	NERC, 2018. Appraising the interaction of NERC marine science with the environment.	NERC, 2018. Appraising the interaction of NERC marine science with the environment.	NERC, 2018. Appraising the interaction of NERC marine science with the environment.
Visual monitoring	1 MMO available on any watch. Certified to JNCC standards. Observations during pre-start and start-up. Pre-start 60 min watch of mitigation zone. For any equipment testing, training or trials activity, at least one MMO present. For any research cruise, at least three MMOs should be part of the sea-going party to enable delivery of the measures 24/7. One of these MMOs (the Lead MMO) should also be trained in PAM.	At least 1 trained MMO. Observations during pre-start and start-up.	General lookout should be kept for species of concern prior to and during the start-up process.
PAM	Certificate of competency issued by a recognised provider. PAM allows survey start-up and repair and maintenance cycles in darkness.	Not mentioned.	Not mentioned.
Mitigation zone	500 m radius from centre of source.	500 m radius from centre of source.	500 m radius from centre of source.
Species	All mammals (marine and coastal) and turtles.	All mammals (marine and coastal) and turtles.	Any mammals (marine and coastal) sensitive to <100 kHz.
Soft-start / ramp-up	20-40 min. Starting at the lowest possible power setting and adopting a progressive and uniform ramp-up in power, if instrumentation allows.	20-40 min. Starting at the lowest possible power setting and adopting a progressive and uniform ramp-up in power, if instrumentation allows.	Not mentioned.

Parameter	Seismic survey	Sub-seabed surveys (sub-bottom profiler)	Parameter
Night/ low visibility	Deploy PAM.	Not mentioned.	Not mentioned.
Other	No requirement to stop once soft-start or full operation has commenced, but is considered best practice to do so if possible.	No requirement to stop once soft-start or full operation has commenced, but is considered best practice to do so if possible.	Not mentioned.

Table E. 2: Example of mitigation procedures adopted by US geophysical surveys in Antarctica.

Parameter	Marine geophysical survey and icebreaking activities
Document specifying mitigation measures	United States Department of Commerce (NOAA, NMFS), 2020. Incidental Harassment Authorization for the THwaites Offshore Research (THOR) Project.
Visual monitoring	At least 3 dedicated, trained NMFS-approved PSOs (at least 1 must have min 90 days experience). Visual observation 30 min prior to ramp-up, during survey operations and 60 mins after acoustic source ceases. Max 4 hr consecutive watch followed by 1 hr break. Max 12 hr observations in 24 hrs. Visual observation when acoustic source is not operating (in daylight sea state ≤3 to compare sightings rates and behaviour). PSO must be equipped with reticule binoculars.
PAM	Not mentioned.
Mitigation zone	Standard: 100 m from edge of airgun array. Special: 500 m for beaked whales, southern right whales, large whales with calf, or an aggregation of large whales.
Species	Protected Species (18 species listed, inc. baleen whales, odontocetes and seals)[27].
Soft-start / ramp-up	No minimum or maximum duration specified. Begins by activating a single airgun of the smallest volume in the array and continues by activating additional airguns at 5-min intervals until full array active.
Night/ low visibility	Night-vision device required for visual obs.

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[27] Potential incidental take authorized for: Blue whale, fin whale, humpback whale, Antarctic minke whale, common (dwarf) minke whale, sei whale, arnoux's beaked whale, killer whale, Layard's beaked whale, long-finned pilot whale, southern bottlenose whale, sperm whale, grays beaked whale, crabeater seal, leopard seal, ross seal, southern elephant seal, weddell seal.

Parameter	Marine geophysical survey and icebreaking activities
	Ramp-up at night or in poor visibility may occur if the relevant mitigation zone has been continually monitored by PSO for 30 mins with no detections.
Other	Shut-down if authorized species in exclusion zone or if non authorized species observed.

Table E. 3: Examples of mitigation procedures adopted by Australian geophysical surveys in Antarctica.

Parameter	Seismic surveys (< 160dB re 1µPa2·s, for 95% of shots @ 1km)	Seismic surveys (all others)
Document specifying mitigation measures	Australian Government Department of the Environment, Water, Heritage and the Arts, 2008. EPBC Act Policy Statement 2.1 – Interaction between offshore seismic exploration and whales.	Australian Government Department of the Environment, Water, Heritage and the Arts, 2008. EPBC Act Policy Statement 2.1 – Interaction between offshore seismic exploration and whales.
Visual monitoring	Trained crew. 30 min observations prior to soft-start.	Trained crew. 30 min observations prior to soft-start.
PAM	Additional method – noted as particularly useful during night-time or low vis.	Additional method – noted as particularly useful during night-time or low vis.
Mitigation zone	Observation zone: 3+ km Low power zone: 1 km Shut-down zone: 500 m	Observation zone: 3+ km Low power zone: 2 km Shut-down zone: 500 m
Species	'Whales' – includes baleen whales and larger toothed whales.	'Whales' – includes baleen whales and larger toothed whales.
Soft-start / ramp-up	30 min. Initiate by firing a single airgun (smallest in terms of energy output and volume preferred); additional components should gradually be added in sequence until operating level is achieved.	30 min. Initiate by firing a single airgun (smallest in terms of energy output and volume preferred); additional components should gradually be added in sequence until operating level is achieved.
Night/ low visibility	Night: start-up if <3 whale instigated power-downs or shut-downs in last 24 hrs.	Night: start-up if <3 whale instigated power-downs or shut-downs in last 24 hrs.
Other	Spotter vessels and aircraft.	Spotter vessels and aircraft.

Parameter	Seismic surveys (< 160dB re 1µPa2·s, for 95% of shots @ 1km)	Seismic surveys (all others)
	Additional MMO if mm in observation zone. Power-down if mm is in low-power zone. Shut-down if mm in shut-down zone.	Additional MMO if mm in observation zone. Power-down if mm is in low-power zone. Shut-down if mm in shut-down zone.

Table E. 4: Examples of mitigation procedures adopted by Australian geophysical surveys in Antarctica.

Parameter	Seismic survey
Document specifying mitigation measures	Umweltbundesamt, 2017. Genehmigung aufgrund des Gesetzes zur Ausführung des Umweltschutzprotokolls vom 4. Oktober 1991 zum Antarktis-Vertrag (AUG)
Visual monitoring	60 min watch prior to ramp-up. 6x MMOs (2 teams of 3, swap every 2 hrs). Supported by helicopter team if weather permits and no other projects are necessarily to be carried out (Note: helicopter has not been used for this purpose to date).
PAM	Static mooring deployed for noise measurement, but not real-time detection.
Mitigation zone	Shutdown zones: 1 km for whales 200 m or 400 m for seals (depending on source and pulse) Precautionary 100 m shutdown zone for MBES and SBP.
Species	Whales and seals (esp beaked whale and southern elephant seal)
Soft-start / ramp-up	Dependent on the specific airgun configuration and technical airgun specifications (e.g. 60 mins for 8 x G-Gun cluster) conducted by an incremental increase of the number of airguns, beginning with a single airgun and subsequently adding one airgun after another within the defined ramp-up time until the full array or cluster is in operation at the end of the ramp-up time (see Boebel et al. 2009).
Night/ low visibility	Mounted thermal IR system.
Other	Profiles conducted from ice edge towards open water. Shut down if animal in exclusion zone. Shut down if beaked whale detected (any distance).

E.5 Summary of key strengths and limitations of approaches to real-time mitigation monitoring, and associated recommendations

From the literature resources examined and the targeted interviews, information was compiled on the effectiveness of different approaches to real-time mitigation monitoring, practical challenges associated with their implementation, along with their key strengths and limitations, and circumstances in which they are more or less suitable (Section E.2). This information is summarised in Sections E.5.1 to E.5.4 below.

E.5.1 Visual monitoring

In good visibility and sea conditions, visual monitoring using trained observers provides an effective tool for detecting many marine mammal species at and above the sea-surface and provides the primary method of monitoring for mitigation in geophysical survey.

- The effectiveness of visual monitoring is species-specific. It is most-effective for short-diving large animals (e.g. baleen whales), or smaller animals which are gregarious and/or highly active at the surface (e.g. delphinids), and least effective for smaller and/or more cryptic surfacing species (e.g. porpoises, beaked whales) and those which perform long, deep-dives (e.g. beaked whales, sperm whales).
- Visual observations cannot be conducted at night, and are impaired by environmental conditions such as fog, precipitation, high sea states, sun glare or low light.
- Distance estimation is particularly challenging using visual observations alone.
- Visual detection is also dependent on the observer's experience, skill and vigilance, and is reliant upon observers having an appropriate, unobstructed viewpoint.

E.5.2 Electro-optical imaging sensors

- Thermal IR systems have been shown to be an effective method for above-surface marine mammal monitoring in daylight, low light and complete darkness. Well performing systems can detect whale blows beyond 2 km range, are also effective for larger groups of smaller cetaceans, and are also quite robust to the effects of sea state, remaining highly effective up to sea state 4.
- Thermal IR systems can operate as a stand-alone system at night, and as a complement to visual observers in the day to increase detection probability.
- Thermal IR systems require animals to break the sea surface, and so suffer the same limitations for deep-diving or cryptic-surfacing species as visual limitations.
- Detections are accompanied by distance and bearing estimates but can only be classified into species groups.
- With automated detections, breaking waves, birds and small ice chunks can be major sources of false alerts on ship-based thermal IR systems.
- Thermal IR systems, along with all sensors, are strongly negatively affected by moisture in the air such as fog or precipitation.

- Thermal IR systems can be expensive to purchase and install ($20-200K USD depending on the system and number of cameras).
- Light-amplifying systems (i.e. night-vision goggles) cannot operate in total darkness. Their effective range and circumstances in which they may be used are limited, therefore limiting their development as a mitigation tool.

E.5.3 Passive acoustic monitoring

- The effectiveness of PAM for real-time monitoring for mitigation purposes varies considerably between species. It can work well with most odontocete species, although the detection range for species which vocalise at very high frequencies (e.g. porpoise) may be small.
- Due to masking and the low vocalisation rates of many baleen whales and seals, the effectiveness of towed PAM for real-time mitigation of this species group is very limited.
- Key strengths of PAM are that it does not rely on animals breaking the sea surface, and therefore can be more effective than visual or imaging systems (e.g. thermal IR) at detecting frequently vocalising species which spend prolonged periods underwater, such as deep diving odontocetes.
- PAM is not affected by fog or low/no light and is far less negatively affected by precipitation or high sea states than visual observations.
- A key challenge in the implementation of towed PAM for mitigation monitoring is vessel noise masking biological sounds, especially low-frequency vocalisations of some baleen whales such as fin and blue whales.
- Sinking the hydrophone array as deep as practicable and maximising the distance between the vessel and the hydrophones can reduce the influence of vessel noise to some extent.
- Deploying towed PAM from an alternative platform to the survey vessel may reduce masking.
- Integrated towed PAM arrays may further mitigate the effects of vessel noise masking and reduce the logistical complexity and entanglement risk associated with ancillary arrays. These systems are not yet widely used commercially or in research applications.
- Other key challenges for using PAM for real-time mitigation include: accurately localising detections in a sufficiently timely manner; a lack of calibration of hydrophones and information on their sensitivity and detection range in commercial applications; operator experience; and, the risk of entanglement with the source array.

E.5.4 Separate unmanned platforms

- Unmanned systems are untested in applications for real-time mitigation monitoring but bring potential into this field.
- Systems would need to operate for long enough periods and cover wide enough ranges to meet the temporal and spatial requirements of the various guidelines.

- Powered ASVs with PAM systems likely present the most promising unmanned system for real-time acoustic detections.
- For UAS, there will be trade-offs between field of view and resolution, and payload and endurance for powered systems.
- The use of thermal IR sensors on UAS would facilitate night-time monitoring, but all sensors would be negatively impacted by fog or precipitation.
- Unmanned systems would require additional trained personnel to those already undertaking visual observations.

E.6 Key challenges in Antarctic waters

The strongest recurring theme among interviewees who had been involved in marine mammal monitoring in Antarctic waters was that weather conditions, including frequent high sea states, precipitation and extreme cold, present one of the biggest challenges to visual monitoring. Such conditions make detection of animals challenging and present logistical challenges in terms of the positioning (inside or outside) of observers, having a sufficient number of observers to be regularly rotated, and having enough space on the vessel for multiple observers. It was also noted that fog and precipitation were common, highlighting the value of PAM as a low-visibility monitoring tool for many odontocete species if geophysical surveys are to continue in such conditions.

Thermal IR systems have been shown to work well in cold environments and be somewhat robust to higher sea states, and are particularly well-suited to large whales, which are regularly encountered in Antarctic waters. The automated detection element of thermal IR system provides a valuable supplement to visual monitoring given challenges associated with cold temperatures.

Towed PAM can provide a useful tool for real-time detection of many odontocete species which may be encountered in Antarctic waters, particularly areas where deep-divers such as sperm and beaked whales may occur. However, masking from vessel noise is understood to be particularly bad for some polar vessels which may limit the effectiveness of towed PAM for all species groups. Deploying a towed PAM array from a second manned vessel is unlikely to be an option in Antarctica. The presence of sea ice may add logistical complexity and risk to deployment of ancillary PAM arrays and also the use of unmanned platforms for deployment.

The presence of ice may represent a greater risk to the safe operation of an unmanned platform such as an ASV or AUV, and an ASV would not be suitable for deployment in advance of a vessel when operating in sea ice. Challenges to the use of UAS systems for mitigation in Antarctic waters include the influence of cold temperatures on battery endurance, and poor weather may present logistical challenges for safe operation. All unmanned systems are untested as real-time mitigation monitoring tools, and would require extensive development and testing, perhaps initially in less-challenging conditions than those presented by Antarctic waters.

E.7 Discussion and recommendations

Each method described in this review has distinct strengths and limitations, and the extent to which they will contribute to effective monitoring will vary according to the circumstances and objectives to which they are applied, including the target species, required detection range and environmental conditions.

Given the variable effectiveness of the different methods of monitoring for marine mammals, it seems logical to combine technology to maximise detection probability for a range of potential conditions and circumstances. For example, in good visibility, the use of visual monitoring supplemented by a thermal IR or PAM system should increase detections across all species, with PAM facilitating the improved detection of long/deep-diving odontocetes in particular. Both PAM and thermal IR allow detections during hours of darkness, and can increase detections in moderate sea states, with thermal IR shown to be effective for baleen whales, and PAM being stronger for most odontocetes. In periods of higher sea states, fog or precipitation, PAM offers a method of detecting of vocalising animals where visual observations or thermal IR may be ineffective. As one interviewee expressed: there is no one perfect tool; using a functional suite should be recommended, particularly for sensitive areas.

Therefore, based on the current stage of development of these different methods, a combination of visual monitoring, vessel-mounted thermal IR system and appropriate towed PAM is recommended as the most effective approach to optimise real-time mitigation monitoring for geophysical survey. It is acknowledged that such a suite of monitoring tools requires considerable resources, including investment in equipment and multiple trained personnel, and that the level of monitoring should be proportional to the activity being undertaken and the sensitivity of the area and species present. It is also recognised that in some circumstances, the use of a towed PAM array may be ineffective due to excessive masking by vessel noise; in such cases, as far as is safe and practicable, alternative platforms for deploying the PAM array should be investigated.

Specific recommendations identified in this review include:

- Design vessels such that the bridge provides as close to unobstructed 360° viewpoint as possible, and with ample suitable space on the vessel for monitoring stations for thermal-IR and/or PAM systems, be these on the bridge or elsewhere, but connected to observers on the bridge by effective communication systems.
- Ensure any unmanned platforms are suitable for operation in cold temperatures, rough sea conditions and potential presence of sea ice. Existing devices may need to be 'ruggedised'.
- Any new technology used as a mitigation tool needs to be carefully selected and calibrated to the specific application. Users require appropriate training, including the creation of manuals for kit and procedures.
- Where berths for dedicated MMOs are limited (as is often the case on Antarctic voyages), the addition of a thermal IR system, along with appropriate training of crew members, can provided a valuable supplement to visual monitoring.
- Further efforts to refine automated detection algorithms for thermal IR systems are required to reduce the influence of false positives, particularly from birds in the air and on the water.
- When setting up a thermal IR-driven automated detection system, a balance needs to be struck between the sensitivity of detection algorithms and the number of false positives an operator can handle. Where the number of false positives is high, more than one dedicated operator is recommended.

- Visual monitoring, thermal IR and other spectral camera systems are all severely impacted by fog and precipitation. In environments where such conditions are common, a PAM system is strongly recommended.
- Any new application of an unmanned autonomous system as a real-time mitigation monitoring tool should undergo extensive testing prior to operational use, as has been done for thermal IR.

E.8 Appendix 1 to Annex 5 - Interviewee list and relevant experience

Table E. 5: List of interviewees and relevant experience.

Name[28]	Current role / affiliation Relevant experience
Brian Miller	Marine mammal acoustician, Australian Antarctic Division. Research focused on passive acoustic population surveys, localisation and tracking, particularly in the Southern Ocean.
Daniel Zitterbart	Principal Investigator - Marine Animal Remote Sensing Group, Woods Hole Oceanographic Institution. Development of thermal IR systems for automatic detection of marine mammals, including in Antarctic environments and in relation to mitigation for geophysical survey.
Anonymous	Biologist with experience of conducting marine mammal research and implementing mitigation for geophysical surveys in Antarctic waters.
Felix Smith	Experienced MMO/PAM-operator, including for seismic and other geophysical surveys. Worked across multiple regions, monitoring tools and mitigation guidelines.
Karsten Gohl	Senior geophysical scientist with the Alfred Wegener Institute Helmholtz-Centre for Polar and Marine Research. Much experience conducting seismic surveys in Antarctic waters with RV *Polarstern*, including marine mammal mitigation procedures.
Klaus Lucke	Senior bioacoustician with JASCO Applied Sciences (Australia), with research focussed on the effects of underwater sound on marine fauna, mitigation of sound-induced effects and regulation of underwater sound.
Anonymous	Marine mammal biologist with experience in conducting marine mammal research surveys in Antarctic waters and working as a marine mammal observer in other areas.
Lorenzo Scala	Bioscience Project Manager, Seiche. Development, implementation and technical support for PAM and thermal IR systems; experienced MMO/PAM-operator with experience in the Arctic.
Neil Niru Dorrian	Experienced MMO/PAM-operator, marine mammal biologist and senior environmental advisor, including for marine construction projects, baseline, seismic, and other geophysical surveys. Worked across multiple regions, utilising various monitoring tools and mitigation guidelines. Has managed comprehensive mitigation and monitoring programs for seismic surveys

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[28] Notes: Interviewees contributed to this study as individuals, rather than representatives of their current affiliation or a specific organisation.

Name[28]	Current role / affiliation Relevant experience
	including one off Sakhalin in 2018. Chair of the Marine Mammal Observers Association 2016-2021.
Patrick Lyne	Experienced MMO/PAM-operator, including for seismic and other geophysical surveys. Worked across multiple regions, monitoring tools and mitigation guidelines, including the development of mitigation protocols and programmes.
Randal Counihan	Experienced MMO/PAM-operator, including for seismic and other geophysical surveys. Worked across multiple regions, monitoring tools and mitigation guidelines.
Robert Larter	A marine geophysicist with British Antarctic Survey. Several decades experience conducting geophysical surveys in Antarctic waters. Member of the Scientific Committee on Antarctic Research ad hoc Group on Marine Acoustic Technology and the Environment (2001-2005). Contributed to developing the 2018 NERC Marine Environment Interaction Policy.

E.9 Appendix 2 to Annex 5 - Interviewee input related to visual monitoring

Table E. 6: Detailed interviewee input related to visual monitoring.

Visual monitoring: interviewee input
Multiple interviewees raised concerns over inaccuracies in estimating distances to animals, or between animals and the source, and therefore uncertainties in their position relative to pre-defined mitigation zones. This is crucial as it determines the decision to postpone or stop survey activities. Distance measuring sticks and reticule binoculars can be subject to considerable error; testing of these (and unaided visual estimates of distance) can be done with objects at known distances such as passing vessels (using ships radar) to calibrate and add confidence. It was also noted that accuracy in distance estimation is related to height above sea-level, and on many vessels this may be a limitation.
Several interviewees expressed limited success with using laser rangefinders in a mitigation monitoring situation. It was expressed that getting a range estimate was difficult, even for relatively large objects in good conditions and within a couple of hundred metres; this was suggested to be attributable to the typically small targets and quick movement of marine mammals, along with the movement of water and ship.
One interviewee noted that with cross-winds or current, the heading of ship will differ to that of its true course (over ground); use of the latter can result in routine errors in estimating an animal's distance to the sound source.
Several interviewees noted that large baleen whales, due to their blow, were the group of marine mammals that could be detected at the greatest range by visual observations alone – with animals regularly sighted at several kilometres range in Bft ≤ 4, but that sighting rates dropped off quickly at higher sea states. One experienced MMO suggested that dolphins (small groups) and medium-sized cetaceans were regularly sighted to 1 km, with porpoise not reliably sighted beyond 500 m.
Two interviewees noted that in circumstances where animals could be detected to a considerable distance ahead of a survey vessel (e.g. the blow of large baleen whales, or a herd of dugong in good conditions), it might be possible to adjust the survey design (e.g. switch lines) to avoid animals and reduce the likelihood of a shutdown. It was noted that this was reliant on an amenable party chief and was likely to require being written into the mitigation plan to guarantee that it would be followed.

Visual monitoring: interviewee input

Interviewees noted that while gaining an unobstructed view from within a vessel could be challenging, bridges on modern vessels were generally pretty good from a visibility perspective. One interviewee noted an example of the *RV Investigator* (Australia), where the bridge is located 20 metres above sea level and provides a 360-degree view around the vessel, with port and starboard wings, a bathroom and desk space.

One interviewee expressed that regulators often specify the location on the vessel from where observations should be made, but this is not always the best; there should always be scope for the observer to decide the best place.

With specific regard to visual monitoring in Antarctica, the following challenges were noted:

- Weather and sea conditions are often challenging for visual monitoring
- Sea states are often high (i.e. Bft 4 or above and with significant ground swell). While baleen whales can still be somewhat reliably detected in such conditions, species identification can be challenging, particularly where wind quickly disperses the blow. Detecting and identifying smaller or more cryptic species is particularly challenging, and smaller species may only be detected when in close proximity to the vessel.
- While science teams want to operate seismic equipment in the calmest conditions possible, they often must compromise to make use of what is available (within safety and equipment limits), with Bft 5-6 being about the limit of operation.
- Poor visibility from fog and precipitation is common.
- Conducting visual observations outside is generally preferable (but dependent on configuration of vessel) to maximise the detection efficiency, but the low temperatures (including wind chill) are challenging and therefore the time an observer can be on watch is considerably less than that would be possible in warmer conditions. There may be health and safety restrictions on the maximum time spent outside on deck.

Geophysical surveys are sometimes conducted in partial sea ice cover, which can often vary between open water and a high percentage of sea ice cover over a relatively short period of time / distance. While sea ice may obscure animals and provide a distraction for visual observers, one interviewee felt that it could provide a useful visual reference point when estimating distance and tracking animals. It was noted that seals are much easier to detect when on sea ice, and the sighting of a seal on ice often alerts the observer to the probability of seals nearby in the water, which can aid detection.

- Crew can be properly trained to act as MMOs (vs dedicated) where berths are limited.
- A keen eye and motivation are the most important attributes.
- To trigger mitigation, it is often not necessary to know the exact species or how they behave, but just recognising whether it is a cetacean or a seal and be able to judge distance is sufficient.

Working within the bridge of the vessel mitigates issues of cold and the need to rotate observers regularly, but, depending on the vessel, the view is often obstructed in one or more directions. This may be less of an issue on more modern vessels designed for polar research, but was noted to be a key problem when using a former fishing vessel.

Operations occur during the Austral summer, so periods of low-light are often limited. However, when operating in areas of sea ice, activities often target late summer (Feb-Mar), by which time there are significant hours of darkness/twilight.

Table E. 7: **Detailed interviewee input related to electro-optical imaging sensors.**

Electro-optical imaging sensors: interviewee input	
General	A well-set-up camera system (thermal IR or other sensor) providing wide coverage around the vessel can be hugely beneficial to supplement visual observations when visibility of the MMO is limited by the ship. When using IR sensors, it can take a while to become familiar with what animals looks like – prior experience is important. With all camera systems, having technical support readily available is very beneficial. Camera systems which record imagery are useful for subsequent review of a sighting for further details on species group, group size. When setting up a camera system for mitigation monitoring, it is important to optimise angles and panning parameters in order to ensure that there is good peripheral vision, no/minimal blind spots, and avoid looking so close to the vessel that imagery suffers from the distraction of lots of water movement. Mounted camera systems have the potential to be very affected by vessel movement and require an appropriate stabilisation system.
Thermal IR systems	Several interviewees (professional MMOs) noted hand-held thermal IR to be of very limited effectiveness due to the small screen and limited field of view. This was in contrast to mounted thermal IR systems, which were considered to be far superior. Multiple interviewees noted that mounted thermal IR systems were very effective for baleen whales, with blows seen at multiple kilometre distances. In operational use, the systems regularly result in initial sightings which are subsequently followed-up by visual observations. They provide a good complement to passive acoustic monitoring for odontocetes. Very effective for detecting pinnipeds on ice. Can be effective for smaller species where they are surface-active (e.g. hourglass dolphins) as this provides a reasonable cue for detection. Multiple interviewees noted that thermal IR systems are strongly affected by moisture in the air and are not effective in fog. Thermal IR systems may be less affected by haze than human observers, as the particles in the air are so small, but scattering occurs once particles get larger (e.g. fog) and the system is no longer effective. Wave crests often come up with the 'hot colour' and this is distracting. The height of the camera is a key factor in determining the detection distance. When setting up a thermal IR-driven automated detection system, a balance needs to be struck between the sensitivity of detection algorithms and the number of false positives an operator can handle. For example, a dedicated operator in a dark room (i.e. with few distractions) can process a higher number of false positives than a non-dedicated crew member who may be working on other tasks simultaneously.

Electro-optical imaging sensors: interviewee input	
	One interviewee described use of a mounted thermal IR system (on RV *Polarstern*) for mitigation in practice. • Their camera system uses tablet computers as an interface; an alert is given when the system makes a detection, and provides an angle, distance and snippet of imagery to review. It is common to follow-up on the detection with visual observation. • During daylight and good sighting conditions, the MMO on the bridge has the tablet. If few detections are being made, the observer on bridge can monitor the tablet and conduct visual observations. But where there are frequent detections, it can be necessary to have a second or dedicated person monitoring the tablet. • Thermal IR is supplemental to visual observers in the day, then at night it is the only system used, with two people monitoring detections on the tablets. For night-time detections the blow and distance would be noted, and shutdown would be initiated if necessary. In some circumstances it may be possible to follow-up the detection with visual observations to check distance and get species ID from the lights of the vessel.
Light-amplifying / night vision goggles	Interviewees with experience using these for low-light observations shared mixed experiences. For higher specification equipment with a fairly wide field of view ('Armasight' products were noted), they were considered to be a useful tool for low-light observations, but much less so for cheaper equipment. It was noted that on a dark night (e.g. overcast; no moon), light-intensifier googles were generally only effective to a few hundred metres distance as they rely upon some ambient light (i.e. from ship). One interviewee suggested that on a brighter night (e.g. clear night with moonlight) and in good conditions, a large whale blow might be seen at several kilometres. Conversely, too much light can impact their effectiveness; for example, they might be ineffective looking to the stern of the vessel due to lots of lighting on the deck. They are fatiguing after a while; could not be used continuously over a three-hour shift, for example: harder to judge distance than with the naked eye in daylight, severely impacted by moisture in the air.

Table E. 8: Detailed interviewee input related to passive acoustic monitoring.

Passive acoustic monitoring: interviewee input	
General	Multiple interviewees note that PAM is only suitable for species and circumstances with regular vocalisations. Not all species vocalise frequently. One interviewee expressed that one of the biggest issues in commercial applications of PAM for mitigation is operator experience. A lack of experience could result in detections errors, improper equipment deployment and potential damage to equipment. It is preferable for PAM to be configured to target the specific species of interest, with the correct sensitivity at the right frequency.
Towed PAM	A key challenge is vessel noise masking biological sounds, especially the low-frequency vocalisations of baleen whales such as fin and blue whales. One interviewee involved in the development of PAM arrays for commercial applications noted that, even with hydrophones sensitive to 10 Hz, it is almost unheard of to detect the lowest-frequency baleen whales from a towed ancillary array due to vessel noise masking.

Passive acoustic monitoring: interviewee input	
	In the North Atlantic, dolphins are generally what is picked up the most (very vocal and come close to the boat). Seals do vocalise and can be picked up by towed PAM but are rarely seen in groups and are rarely vocalising. On larger vessels, noise from the ship's wash/wake can also be a considerable source of masking for a towed PAM array. Several interviewees described carefully attaching a small amount of weight to the array cable, to sink the array to a greater depth than it usually sits (e.g. 20+ m), which greatly reduces noise from the wash. It was noted that there is a risk of a PAM array breaking due to weights being added, although arrays now appear to be stronger than they used to be; one interviewee mentioned use of a chain (8-10 kg), while another described a shaped weight to reduce drag. One interviewee noted that towed PAM systems might not be suitable in circumstances such as particularly noisy (often old) vessels or in very shallow waters, where it is not possible to sink the array more than a few metres. It was also noted that logistical or safety considerations on particular vessels may prohibit the use of a supplemental towed array (e.g. RV *Polarstern*). In commercial settings, it is not always clear what the sensitivity and detection range of the hydrophones is – this is not always provided by PAM manufacturers and can differ between kit. This is important to know if the equipment is appropriate for detecting the species of interest. Several interviewees noted the difficulty of animal localisation from a towed PAM array and therefore estimating distances of animals to the array. While animal localisation is possible within the associated software (PAMGuard), it requires the correct configuration of hydrophones within the array, and there is uncertainty over how different configurations affect the efficacy and accuracy of animal localisations (for example, see BOEM project: **"Optimization of Towed Passive Acoustic Monitoring (PAM) Array Design and Performance (AT-19-02)"**. Several interviewees mentioned awareness of the Sercel 'Quiet Sea' PAM system integrated into streamers, but there was limited experience in its use. One interviewee reported that the system had been ineffective on RV *Polarstern* due to high vessel noise, but that he was aware that deployments on other, quieter vessels (*RV Sonne*, *RV Maria S. Merian*) had resulted in detections.
Static PAM	It was noted that the acoustic properties of Antarctic waters are fairly unique in terms of the sound speed profile, lack of land obstructions in the Southern Ocean, and the presence of surface ice. Sound can travel over particularly long ranges. One interviewee described an application in Irish waters where two PAM buoys were moored at either end of a dredge spoil dumping site. A summary of click detections was sent at regular intervals (e.g. every 2 minutes) to the dredge vessel. Where detections occurred, these were accompanied by spectrogram snapshots were provided to allow for differentiation of true detections and false positives. This informed the location of dredge spoil dumping, with the vessel avoiding dumping dredge spoil at the location where animals were recently detected, where possible. This procedure was considered best practice rather than a mandatory condition. One interviewee noted that while static or drifting buoys for real-time PAM could be used as monitoring for mitigation, these are generally bespoke and not widely used at present.

Passive acoustic monitoring: interviewee input	
	Continued development of telemetry systems (e.g. satellite or wifi link to vessels) may increase the use of static PAM for mitigation. One interviewee noted that drifting buoys (specifically sonobuoys) do not suffer from the masking effect of ship noise (unless ship is in close proximity) as they are not attached to the ship. By positioning the hydrophone at depth (e.g. ≥ 30 m) and using a design that minimises movement of the hydrophone, it is also possible to avoid significant surface and self-noise, even in high sea states (e.g. up to SS 7). One interviewee noted that where moored static PAM includes real-time VHF transmission of data from a surface buoy, it is necessary to maintain line of sight. Particular consideration needs to be given to the mooring design when operating in areas of high current or rough seas to ensure the VHF antennae remains upright. Not for real-time detection, but the deployment of static PAM at the start of a survey to do sound source verification can be a valuable tool in validating mitigation zones, particularly where there is uncertainty over the source characteristics and its propagation.

Table E. 9: Detailed interviewee input related to separate unmanned platforms.

Separate unmanned platforms: interviewee input

A single interviewee had experience with using Autonomous Surface Vehicles (ASV) for passive acoustic monitoring, albeit not in a mitigation application:

- The interviewee shared their experiences with the AutoNaut – a self-powered (by waves) ASV with a PAM system integrated. The ASV is controlled via satellite (iridium). PAM data are typically archived and then downloaded when retrieved or brought within WiFi range (up to 5 km). Such a device could be set-up for real-time PAM, but it is better suited for remote deployments with data archival.
- In terms of potential for providing an alternative platform for PAM to transit in front of a geophysical survey vessel, self-powered vehicles would not be suitable as their average speed is too low (e.g. 0.5-2 knots for the AutoNaut, depending on wave height).
- A self-powered USV could, however, be used to monitor the perimeter of a survey area or conduct a ‘pre-survey sweep’ to inform mitigation such as fine-scale survey design at the operational stage. An application was described where the AutoNaut was deployed for approximately 50 continuous days during offshore works, with a pre-determined course updated via satellite and data downloaded daily when brought in wifi range of a mother ship.
- A better system for real-time PAM, which could potentially be used to detect marine mammals in advance of a survey vessel, would be a fuel-powered ASV that could achieve sufficient speed. PAM systems have been incorporated into these, and data can be sent to the survey vessel in real-time via wifi link.
- It was noted that ASVs provide much quieter platforms than geophysical survey vessel, with self-powered ASVs being the quietest.
- With specific regard to Antarctic waters, it was noted that ASVs would need to be made more robust than those used elsewhere. This had been done previously with an AutoNaut which had been fitted with a mechanism to carry and launch a glider, to provide a low-cost alternative to a vessel to transport and deploy a glider in a remote area.

One other interviewer noted the challenges involved in a seismic vessel deploying / retrieving an unmanned vehicle. Deploying would be straightforward, but it would be extremely challenging / not possible to retrieve the vehicle with airguns and streamers deployed due to the restricted mobility of the

Separate unmanned platforms: interviewee input
vessel; there would be a risk of failed retrieval and entanglement with the array. Deploying from a second vessel would eliminate these problems but Antarctic voyages are single vessels only; it is possible that some unmanned vehicles might be deployed and retrieved from a ship's tender vessel. No other interviewees shared experience or perspectives on aerial or other unmanned platforms in a detection for mitigation context.

Table E. 10: Detailed interviewee input related to separate unmanned platforms.

Induced avoidance from soft-start: Interviewee input
One interviewee noted potential shortcomings in the way seismic airgun array soft-starts (ramp-ups) are typically implemented. It was noted that, in practice, the number of active airguns is typically increased one at a time from a single airgun to the full array, particularly where the soft-start is controlled automatically by a programme (e.g. Gunlink or Nucleus). Guidelines published by the International Association of Oil & Gas Producers (IOGP 2017) specify a doubling of the number of active elements (airguns) at each stage, which should result in an approximate 6 dB rise in sound pressure level (a doubling of the amplitude). Adding one airgun per stage (vs doubling the number active) results in a diminishing increase in sound levels at each stage, which may be not be discernible to animals as an increase in volume and therefore not have the desired effect of displacing animals from the zone of potential auditory injury. The interviewee recommended adherence to the IOGP (2017) guidelines, noting that this is likely to require a manually controlled soft-start. It was also noted that it may be worth modelling the source to estimate the anticipated increase in sound levels with the addition of different numbers of airguns, and consequently implement a soft-start accordingly.
One interviewee expressed that the efficacy of soft-starts has not been proven; however, considering the time taken to deploy an airgun array (1-2 hours in a research capacity, longer for a commercial array), implementing a soft-start was not a burden on a survey.

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