



Managing the Effects of Noise From Ship Traffic, Seismic Surveying and Construction on Marine Mammals in Antarctica

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The Protocol on Environmental Protection of the Antarctic Treaty stipulates that the protection of the Antarctic environment and associated ecosystems be fundamentally considered in the planning and conducting of all activities in the Antarctic Treaty area. One of the key pollutants created by human activities in the Antarctic is noise, which is primarily caused by ship traffic (from tourism, fisheries, and research), but also by geophysical research (e.g., seismic surveys) and by research station support activities (including construction). Arguably, amongst the species most vulnerable to noise are marine mammals since they specialize in using sound for communication, navigation and foraging, and therefore have evolved the highest auditory sensitivity among marine organisms. Reported effects of noise on marine mammals in lower-latitude oceans include stress, behavioral changes such as avoidance, auditory masking, hearing threshold shifts, and—in extreme cases—death. Eight mysticete species, 10 odontocete species, and six pinniped species occur south of 60°S (i.e., in the Southern or Antarctic Ocean). For many of these, the Southern Ocean is a key area for foraging and reproduction. Yet, little is known about how these species are affected by noise. We review the current prevalence of anthropogenic noise and the distribution of marine mammals in the Southern Ocean, and the current research gaps that prevent us from accurately assessing noise impacts on Antarctic marine mammals. A questionnaire given to 29 international experts on marine mammals revealed a variety of research needs. Those that received the highest rankings were (1) improved data on abundance and distribution of Antarctic marine mammals, (2) hearing data for Antarctic marine mammals, in particular a mysticete audiogram, and (3) an assessment of the effectiveness of various noise mitigation options. The management need with the highest

score was a refinement of noise exposure criteria. Environmental evaluations are a requirement before conducting activities in the Antarctic. Because of a lack of scientific data on impacts, requirements and noise thresholds often vary between countries that conduct these evaluations, leading to different standards across countries. Addressing the identified research needs will help to implement informed and reasonable thresholds for noise production in the Antarctic and help to protect the Antarctic environment.

Keywords: underwater noise, Antarctica, marine mammal, Antarctic Treaty, ship, seismic survey, noise management

INTRODUCTION

The Antarctic Treaty was established for the protection of the Antarctic, allowing scientific research but prohibiting military activity. It entered into force in 1961 and has since been signed by 53 Parties. Its Protocol on Environmental Protection (the Protocol) entered into force in 1998, stipulating that the protection of the Antarctic environment and associated ecosystems be fundamentally considered in the planning and conducting of all activities in the Antarctic Treaty area (area south of 60°S, i.e., approximately south of the Antarctic Convergence, including all ice shelves). While fishing was deemed allowable by the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) in 1982, the Protocol prohibits all activities relating to Antarctic mineral and hydrocarbon resources, except for scientific research.

Parties implement the Protocol via national acts and laws. For example, in Germany, the Act Implementing the Protocol on Environmental Protection to the Antarctic Treaty (AIEP, 1998) identifies the German Environment Agency (Umweltbundesamt, UBA) as the competent authority for assessing and permitting German activities in the Antarctic. The AIEP and the Protocol protect native animals at individual and population levels. Activities that molest, handle, capture, injure or kill a native mammal or bird are prohibited (Annex II to the Protocol). However, exceptions can be granted for scientific or educational purposes. A permit cannot be issued if the activity is suspected to cause (a) harmful changes to the distribution, abundance or productivity of an animal species or its populations, (b) threats to endangered species or populations, or (c) significant detrimental effects on the environment and associated ecosystems. Any scientific research that is deemed by UBA to have the potential to create at least a minor or transitory impact is also evaluated by an independent committee of scientific experts (Sachverständigenkommission Antarktis, SV-KOM).

Underwater noise is part of almost all anthropogenic activities in the Antarctic, ranging from ship traffic to construction and scientific seismic surveys (**Figure 1**). Such noise can have profound effects on marine organisms and has been identified as a major stressor in the marine environment (see the collection of articles covering a diversity of species in Popper and Hawkins, 2016). Yet, no specific guidelines for noise production in the Antarctic have been established and noise has only once been considered at the Meetings of the Committee for

Environmental Protection (CEP) since 2012.¹ The CEP normally meets once a year in conjunction with the Antarctic Treaty Consultative Meeting (ATCM) and (a) addresses matters relating to environmental protection and management, (b) provides advice to the ATCM, and (c) formulates measures or resolutions in furtherance of the principles and objectives of the Treaty for the adoption through the ATCM. The Scientific Committee on Antarctic Research (SCAR) is an inter-disciplinary committee of the International Science Council (ISC) and provides scientific advice to the Parties at the ATCM.

Arguably, amongst the species most vulnerable to noise are marine mammals since they specialize in using sound for communication, navigation and foraging, and therefore have evolved sensitive auditory systems (Au et al., 2000). The effects of ship noise on marine mammals have recently been reviewed (Erbe et al., 2019). Knowledge about the effects of noise on marine mammals is mostly based on studies from regions other than the Southern Ocean. Documented effects include potential

¹ATCM 2019, WP 68, “Anthropogenic Noise in the Southern Ocean: an Update,” submitted by SCAR.



FIGURE 1 | Sketch of sources of underwater noise in the Antarctic. All vessels (fishing vessels, cruise ships, research vessels, etc.) produce underwater noise in a nearly omni-directional pattern (indicated by circular sound wavefronts). Ships use echosounders that scan the sea floor with a narrow swatch of sound (indicated in yellow). Research station infrastructure and support includes construction activities, vessels as well as aircraft—all of which may be detected under water.

increases in stress (Rolland et al., 2012), behavioral changes such as short- and long-term avoidance of affected areas (Nowacek et al., 2007; Götz and Janik, 2013), auditory masking (Erbe et al., 2016), hearing threshold shifts (Finneran, 2015), and—in extreme cases—death (Schrope, 2002). Studies conducted outside of the Antarctic have shown that reactions to noise differ widely between marine mammal species (Ellison et al., 2012).

The Southern Ocean is in many ways not comparable to other ocean basins. In terms of biodiversity, the Antarctic is home to a range of marine species that cannot be found elsewhere on the globe. Some species are year-round residents of Antarctic waters, such as the ice-breeding pinniped species. Other species migrate to the Antarctic annually to forage. In fact, the Antarctic is of critical importance to migrating mysticete whales, which come here during the austral summer for feeding. During this time, they take in a large proportion (possibly up to 80%) of their annual energy requirements and store substantial amounts of lipids (some grow their body weight by 30–100%; Brodie, 1975; Lockyer, 1981; Reilly et al., 2004). In terms of acoustics, the marine soundscape of the Southern Ocean is a unique combination of sounds from Antarctic fauna, weather events and ice (plus anthropogenic sounds). Underwater sound propagation is strongly influenced by the low water temperature and ice cover around the Antarctic continent. Thus, we set out to determine the current state of knowledge on the effects of underwater noise on marine mammals in the Antarctic, to identify knowledge gaps, and to discuss research needs.

MARINE MAMMALS IN THE ANTARCTIC

Eight mysticete species (and subspecies), 10 odontocete species, and six pinniped species have been observed south of 60°S (Table 1). Out of these, the Antarctic blue whale is listed by the International Union for Conservation of Nature and Natural Resources (IUCN; iucnredlist.org) as “critically endangered,” the pygmy blue whale, fin whale, and sei whale are listed as “endangered,” the Antarctic minke whale is “near threatened,” and the sperm whale is “vulnerable.” Arnoux’s, Gray’s, and strap-toothed beaked whales, as well as the killer whale are data deficient; so their conservation status cannot be determined. Other Antarctic marine mammals are currently listed as “least concern.”

With regard to the application and interpretation of the legal regulations relating to the Antarctic Treaty area, it is important to ascertain which marine species are relevant: The Environmental Protocol protects individual members of “native” mammal species and also protects the populations of all animal species, including sporadically occurring species. In this context, the word “native,” which is used in the Environmental Protocol, has the same meaning as the notion of “true” Antarctic species, as defined in Boyd et al. (2002): “those species whose populations rely on the Southern Ocean as a habitat, i.e., critical to a part of their life history, either through the provision of habitat for breeding or through the provision of the major source of food.” For the Protocol, however, the “native” criterion is only applied to individual members of a species. With regard to

populations, protection is extended to both native and non-native animal species, including those that occur only rarely, such as *Phocoena dioptrica*.

Information on distribution and abundance of Antarctic marine mammals is mostly scarce, although annual surveys were conducted as part of the International Whaling Commission (IWC) circumpolar IDCR/SOWER programs between 1978/79 and 2003/04. These programs surveyed a sector of roughly 60° longitude each year, from the ice edge to 60°S, generating abundance estimates for a number of species including the Antarctic blue whale (Branch, 2007), humpback whale (Branch, 2011), and Antarctic minke whale (IWC, 2013). These and most other visual surveys have been generally confined to ice-free areas and undertaken during the brief austral summer. Information on migrations, spatial distribution, and abundance in ice-covered areas (e.g., Herr et al., 2019) or during other times of the year is limited though growing—for example, as a result of autonomous passive acoustic monitoring, which can collect information on acoustic presence year-round (e.g., Van Opzeeland et al., 2008; Van Parijs et al., 2009). Field research in the Antarctic is expensive and limited in space and time, resulting in numerous data gaps (Table 2).

The available information indicates that blue, fin, humpback, and minke whales are found all the way to the ice edge throughout the austral summer season, with the peak of fin and humpback whale encounters tending to be further away from the ice edge than the highest densities of Antarctic blue and Antarctic minke whales (e.g., Tynan, 1998; Williams et al., 2014b). Passive acoustic observations have shown that Antarctic blue, Antarctic minke, and humpback whale distributions are, however, not limited by ice (van Opzeeland et al., 2013; Dominello and Širović, 2016; Thomisch et al., 2016). Observations of Antarctic minke whales show this species predominantly occurs in areas with dense ice cover (Williams et al., 2014b; Herr et al., 2019). Fin whales are acoustically present year-round in some areas (E. Burkhardt pers. comm.), although in other areas they seem to avoid ice cover (Širović et al., 2004; Herr et al., 2016). Sei and southern right whales are typically not encountered at the ice edge (Kasamatsu et al., 1996; Best, 2007). Killer whales occurring in Antarctic waters comprise four different ecotypes, which all occur beyond the ice edge in pack-ice areas (see de Bruyn et al., 2013 for a review). Southern bottlenose and Arnoux’s beaked whales occur in open water south of 60°S up to the ice edge. Arnoux’s beaked whales have furthermore during summer been observed to occur in pack-ice areas (Best, 2007). Sperm whales, other beaked whales, and the smaller odontocetes are found further away from the ice edge (Kasamatsu and Joyce, 1995). The Antarctic fur seal and the southern elephant seal are ice-tolerant, but open-water species, that generally depend on land for breeding (Boyd et al., 1998; Bornemann et al., 2004; Hindell et al., 2016). The crabeater, leopard, Ross, and Weddell seals also have pelagic phases, but are bound to the presence of sea-ice for breeding and molt, with each species exhibiting different sea-ice habitat requirements (Ropert-Coudert et al., 2014; Siniff, 2015). Distribution maps for marine mammals occurring around Antarctica are shown in the *Biogeographic Atlas of the Southern Ocean* (Ropert-Coudert et al., 2014).

TABLE 1 | Marine mammal species in the Antarctic, based on Roper-Coudert et al. (2014).

Species Latin Name	Species Common Name	IUCN Conservation Status	Sightings <60°S
Mysticetes			
<i>Balaenoptera acutorostrata</i>	Dwarf minke whale	Least concern	common
<i>Balaenoptera bonaerensis</i>	Antarctic minke whale	Near threatened	regular
<i>Balaenoptera borealis</i>	Sei whale	Endangered	common
<i>Balaenoptera musculus brevicauda</i>	Pygmy blue whale	Endangered	rare
<i>Balaenoptera musculus intermedia</i>	Antarctic blue whale	Critically endangered	regular
<i>Balaenoptera physalus</i>	Fin whale	Endangered	regular
<i>Eubalaena australis</i>	Southern right whale	Least concern	common
<i>Megaptera novaeangliae</i>	Humpback whale	Least concern	regular
Odontocetes			
<i>Berardius arnuxii</i>	Arnoux's beaked whale	Data deficient	common
<i>Globicephala melas</i>	Long-finned pilot whale	Least concern	common
<i>Hyperoodon planifrons</i>	Southern bottlenose whale	Least concern	regular
<i>Lagenorhynchus cruciger</i>	Hourglass dolphin	Least concern	common
<i>Mesoplodon grayi</i>	Gray's beaked whale	Data deficient	rare
<i>Mesoplodon layardii</i>	Strap-toothed whale	Data deficient	rare
<i>Orcinus orca</i>	Killer whale	Data deficient	regular
<i>Phocoena dioptrica</i>	Spectacled porpoise	Least concern	rare
<i>Physeter macrocephalus</i>	Sperm whale	Vulnerable	regular
<i>Ziphius cavirostris</i>	Cuvier's beaked whale	Least concern	rare
Pinnipeds			
<i>Arctocephalus gazella</i>	Antarctic fur seal	Least concern	regular
<i>Hydrurga leptonyx</i>	Leopard seal	Least concern	regular
<i>Leptonychotes weddellii</i>	Weddell seal	Least concern	regular
<i>Lobodon carcinophaga</i>	Crabeater seal	Least concern	regular
<i>Mirounga leonina</i>	Southern elephant seal	Least concern	regular
<i>Ommatophoca rossii</i>	Ross seal	Least concern	regular

Reported encounter rates for mysticetes and odontocetes peak in January and February (Kasamatsu and Joyce, 1995; Kasamatsu et al., 1996). Many mysticetes migrate to the Antarctic in the austral summer to feed before they migrate to warmer waters where they breed in the austral winter (Lowther, 2018). There is increasing evidence of mysticete presence in the Antarctic throughout the austral winter from passive acoustic recordings (Sirovic et al., 2009; van Opzeeland et al., 2013; Thomisch et al., 2016). Of odontocetes, some killer whale ecotypes are resident in the Antarctic all year-round (Pitman and Ensor, 2003). Of sperm whales, only males venture this far south and stay over the winter (Kasamatsu and Joyce, 1995). Winter surveys indicate that 20 or more cetacean species have regular, potentially year-round presence in the Antarctic (Thiele and Gill, 1999; Thiele et al., 2004; van Waerebeek et al., 2010). Amongst pinnipeds, elephant seals and Antarctic fur seals forage in the Antarctic in the austral winter, but breed on subantarctic islands like the Kerguelen Islands, Macquarie Island, or South Georgia during the summer (Boyd et al., 2002; Rodríguez et al., 2017). All other Antarctic seal species are ice breeding and are resident in Antarctic waters south of the Antarctic Convergence year-round. However, some of these species, in particular leopard seals, can also be found on subantarctic islands (Lowther, 2018).

Information on the diet of some Antarctic marine mammals is scarce, though data are available for some whale species from

whaling records, and for other species diet can be inferred from the same or related species in other geographic regions (see Pauly et al., 1998 for an overview). The mysticetes feed primarily on krill, but may also take small fish, zooplankton, and possibly squid. The odontocetes eat fish and squid, with certain killer whale ecotypes also hunting penguins and other marine mammals (both cetaceans and pinnipeds). Antarctic pinnipeds forage on krill, fish, zooplankton, and squid, with leopard seals also taking other seals and seabirds. Lowther (2018) provides a recent summary of the diets of Antarctic marine mammals.

Given the potential for anthropogenic activities occurring in Antarctic waters to affect critical life functions of marine mammals, it is imperative for environmental impact assessments to consider impacts on the acoustic habitat of marine mammals. Marine mammals actively and passively use sound in support of their various life functions, as do at least some of their prey species. Sound plays a role in marine mammal behavioral contexts, comprising social encounters, feeding, mother-offspring recognition, and mating (van Opzeeland et al., 2010; Janik, 2014; Reichmuth and Casey, 2014). Odontocetes use active biosonar for navigating and foraging (Au, 1993). All marine mammals likely listen to environmental sounds, as well as the sounds of predators and prey (Gannon et al., 2005; Janik, 2005). Interfering with sound usage and sensing while marine

TABLE 2 | Available information and knowledge gaps regarding Antarctic marine mammals.

		Knowledge on Antarctic abundance, trends, distribution, seasonality (0–5)	Knowledge on behavior while in Antarctica (0–5)	Under-water audio-gram	Data on TTS	Data on PTS	NOAA functional hearing group	Data on stress	Data on masking (e.g., CR)	Impacts of seismic surveying	Impacts of ships, noise and strikes	Impacts of sonar	Other responses to noise	Knowledge of prey species (0–5)	Info on PCoD
Mysticetes															
<i>Balaenoptera acutorostrata</i>	Dwarf minke whale	1 (Cooke, 2018a)	1				LF					Sivle et al., 2015; Kvasdheim et al., 2017	McGarry et al., 2017	2 (Skaug et al., 1997; Kato and Fujise, 2000; Secchi et al., 2003; Perrin and Brownell, 2009)	
<i>Balaenoptera bonaerensis</i>	Antarctic minke whale	3 (Kasamatsu et al., 1996; Leaper et al., 2008a; Bravington and Hedley, 2012; Herr et al., 2019)	2				LF							3 (Armstrong and Siegfried, 1991; Perrin and Brownell, 2009)	
<i>Balaenoptera borealis</i>	Sei whale	2 (Kasamatsu et al., 1996; Leaper et al., 2008a; Horwood, 2009)	1				LF							2 (Baumgartner and Fratantoni, 2008)	
<i>Balaenoptera musculus breviceauda</i>	Pygmy blue whale	2 (Branch, 2007; Branch et al., 2018; Cooke, 2018b)	2				LF							4 (Branch, 2007; Cooke, 2018b)	
<i>Balaenoptera musculus intermedia</i>	Antarctic blue whale	4 (Kasamatsu et al., 1996; Sirovic et al., 2004, 2009; Matsuoka et al., 2006; Branch, 2007; Leaper et al., 2008a; Thomisch et al., 2016; McCauley et al., 2018)	3				LF				Laist et al., 2001; Berman-Kowalewski et al., 2010	Goldbogen et al., 2013		4 (Branch, 2007; Cooke, 2018b)	
<i>Balaenoptera physalus</i>	Fin whale	3 (Gambell, 1985; Kasamatsu et al., 1996; Branch and Butterworth, 2001; Leaper et al., 2008a; Herr et al., 2016)	2				LF			Castellote et al., 2012	Laist et al., 2001; Castellote et al., 2012			2 (Aguilar, 2009)	
<i>Eubalaena australis</i>	Southern right whale	2 (International Whaling Commission, 2001; Leaper et al., 2008a)	2				LF	Rolland et al., 2012			Laist et al., 2001			2 (Kenney, 2009)	

(Continued)

TABLE 2 | Continued

		Knowledge on Antarctic abundance, trends, distribution, seasonality (0–5)	Knowledge on behavior while in Antarctica (0–5)	Under-water audio-gram	Data on TTS	Data on PTS	NOAA functional hearing group	Data on stress	Data on masking (e.g., CR)	Impacts of seismic surveying	Impacts of ships, noise and strikes	Impacts of sonar	Other responses to noise	Knowledge of prey species (0–5)	Info on PCoD
<i>Megaptera novaeangliae</i>	Humpback whale	4 (Kasamatsu et al., 1996; Branch, 2006, 2011; Pastene et al., 2006; Zerbinì et al., 2006; Leaper et al., 2008a; Herr et al., 2016)	3				LF		(Dunlop et al., 2010) Lombard Effect	Dunlop et al., 2017	Laist et al., 2001; Blair et al., 2016	Sivle et al., 2015, 2016		3 (Baraff et al., 1991; Clapham, 2009)	
Odontocetes															
<i>Berardius arnuxii</i>	Arnoux's beaked whale	1 (Friedlaender et al., 2010; van Waerebeek et al., 2010)	1				MF							0	
<i>Globicephala melas</i>	Long-finned pilot whale	2 (Kasamatsu and Joyce, 1995; van Waerebeek et al., 2010)	2	Pacini et al., 2010			MF		(Visser et al., 2016) anti-masking behavior	Stone and Tasker, 2006		Antunes et al., 2014		2 (Gannon et al., 1997; Santos et al., 2014; Monteiro et al., 2015)	
<i>Hyperoodon planifrons</i>	Southern bottlenose whale	1 (Kasamatsu and Joyce, 1995; Branch and Butterworth, 2001)	2				MF							1 (MacLeod et al., 2003)	
<i>Lagenorhynchus cruciger</i>	Hourglass dolphin	1 (Kasamatsu and Joyce, 1995; Goodall, 1997)	1				HF							1 (Fernández et al., 2003; Braulik, 2018)	
<i>Mesoplodon grayi</i>	Gray's beaked whale	1 (van Waerebeek et al., 2010)	1				MF							1 (MacLeod et al., 2003)	
<i>Mesoplodon layardii</i>	Strap-toothed whale	1 (van Waerebeek et al., 2010)	1				MF							1 (Sekiguchi et al., 1996; MacLeod et al., 2003)	
<i>Orcinus orca</i>	Killer whale	3 (Kasamatsu and Joyce, 1995; Gill and Thiele, 1997; Branch and Butterworth, 2001; Leaper et al., 2008b; van Waerebeek et al., 2010)	3	Hall and Johnson, 1972; Szymanski et al., 1999; Branstetter et al., 2017)			MF	Ayres et al., 2012	(Bain and Dahlheim, 1994) spatial masking release, (Holt et al., 2011, 2009) Lombard Effect	Stone and Tasker, 2006	Ayres et al., 2012; Williams et al., 2014a	Miller et al., 2014		3 (Lauriano et al., 2007; Ford, 2009; Pitman and Durban, 2010, 2012)	

(Continued)

TABLE 2 | Continued

		Knowledge on Antarctic abundance, trends, distribution, seasonality (0–5)	Knowledge on behavior while in Antarctica (0–5)	Under-water audio-gram	Data on TTS	Data on PTS	NOAA functional hearing group	Data on stress	Data on masking (e.g., CR)	Impacts of seismic surveying	Impacts of ships, noise and strikes	Impacts of sonar	Other responses to noise	Knowledge of prey species (0–5)	Info on PCoD
<i>Phocoena dioptrica</i>	Spectacled porpoise	1 (Sekiguchi et al., 2006)	0				HF							1 (Natalie et al., 2018)	
<i>Physeter macrocephalus</i>	Sperm whale	3 (Kasamatsu and Joyce, 1995; Whitehead, 2002)	2				MF		Miller et al., 2009	Laist et al., 2001		Curé et al., 2016; Isojunno et al., 2016	Cure et al., 2013	3 (Whitehead, 2009)	
<i>Ziphius cavirostris</i>	Cuvier's beaked whale	1 (van Waerebeek et al., 2010)	1				MF			Aguilar Soto et al., 2006		Fernandez et al., 2005; Krysl et al., 2006; DeRuiter et al., 2013; Falcone et al., 2017		1 (MacLeod et al., 2003)	
Pinnipeds															
<i>Arctocephalus gazella</i>	Antarctic fur seal	3 (Hofmeyr, 2016)	3				OW							4 (Hofmeyr, 2016)	
<i>Hydrurga leptonyx</i>	Leopard seal	1 (Rounsevell and Eberhard, 1980; Borsa, 1990; Rogers, 2009; Southwell et al., 2012)	3				PW							2 (Rogers, 2009; Southwell et al., 2012)	
<i>Leptonychotes weddellii</i>	Weddell seal	1 (Hückstädt, 2015a)	3				PW							2 (Burns et al., 1998)	
<i>Lobodon carcinophaga</i>	Crabeater seal	1 (Hückstädt, 2015b)	3				PW							2 (Hückstädt et al., 2012)	
<i>Mirounga leonina</i>	Southern elephant seal	3 (Murray, 1981; Heimark and Heimark, 1986; Bester, 1988; McCann and Rothery, 1988; Bester and Hofmeyr, 2005; van den Hoff et al., 2007; Hofmeyr, 2015; Hindell et al., 2016)	3				PW							4 (Brown et al., 1999; Piatkowski et al., 2002; Bradshaw et al., 2003; Chereil et al., 2008; Field et al., 2011)	New et al., 2014
<i>Ommatophoca rossii</i>	Ross seal	1 (Hückstädt, 2015c)	2				PW							1 (Southwell et al., 2012)	

The columns relating to available knowledge show a ranking of 0 (none) to 5 (good) by the authors. TTS: Temporary threshold shift. PTS: Permanent threshold shift. NOAA's functional hearing groups are: low-frequency (LF), mid-frequency (MF), high-frequency (HF), otariids in water (OW), and phocids in water (PW). CR: Critical ratio. PCoD: Population Consequences of Disturbance.

mammals undergo critical life functions in the Antarctic can affect individuals and possibly populations in the Antarctic and beyond.

UNDERWATER ANTARCTIC NOISE

Ambient noise in the Antarctic can be of abiotic, biotic, and anthropogenic origin. Wind over open ocean leads to the entrainment of bubbles, which produce a broad spectrum of sound (Knudsen et al., 1948). Wind blowing over ice produces a different spectrum of sound. Wind and currents move ice flows and push icebergs together or against the seabed, resulting in distinct rubbing and cracking sounds, with the former being quite tonal in character (e.g., Gavrilov and Li, 2007). Temperature changes lead to ice cracking, which is typically impulsive and broadband.

Polar waters can be both noisier and quieter than the open ocean. The ice edge typically is an active acoustic zone with high sound levels due to ice breaking, colliding, and shearing (Haver et al., 2017). Conversely, it is quieter under the ice fields during stable conditions (Mikhalevsky, 2001). Marine mammals, fish, and crustaceans produce sound, often prolifically, resulting in continuous choruses in characteristic frequency bands. A multi-year recording at 0°E, 66°S was analyzed to present a statistical analysis of biotic and abiotic ambient noise, as a function of wind speed and ice cover, showing that whale and seal choruses generated distinct peaks in the ambient noise spectra (e.g., Antarctic blue whale chorus at 15–30 Hz, fin whales at 95–105 Hz, minke whales at 90–200 Hz, and leopard seals at 320–350 Hz; Menze et al., 2017).

Anthropogenic underwater noise in the Southern Ocean originates from ships—mostly research vessels, cruise ships, and fishing vessels. During the 2017/2018 austral summer, 98 research stations and 51 research or research support ships were registered with the Council of Managers of National Antarctic Programs (COMNAP)², 53 tourism ships were registered with the International Association of Antarctica Tour Operators (IAATO)³, and 46 fishing vessels reported to the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR)⁴.

The latest season where data from COMNAP, IAATO, and CCAMLR were available for a more detailed analysis was the austral summer of 2016/2017. In terms of the cumulative amount of time spent by these types of vessels, IAATO tourist vessels contributed 3,200 ship-days,⁵ CCAMLR fishing vessels

contributed 1,400 ship-days⁶, and COMNAP research vessels contributed 1,100 ship-days⁷ in the 2016/2017 season. In terms of the total number of people carried into the Antarctic during the 2016/2017 season, cruise ships (73,400 people incl. staff and crew) surpassed research vessels (3,300 people incl. crew) and fishing vessels (2,100 people). In terms of person-days (i.e., the cumulative sum of the number of persons multiplied by the time each spends), research (797,000 person-days at fixed stations plus approximately 100,000 person-days on COMNAP ships) outweighed tourism (730,000 person-days) and fisheries (63,000 person-days).

Since 2015, CCAMLR has required an automated vessel monitoring system (VMS) for all fishing vessels (Commission for the Conservation of Antarctic Marine Living Resources, 2015). While detailed positions of the CCAMLR fishing fleet have been collected since 2015, they are treated as commercially confidential information by the CCAMLR secretariat; so positions for each nation's vessels are only disclosed to the appropriate authority for that contracting nation. Thus, only an aggregate list of vessels licensed by CCAMLR for fishing in the Antarctic is generally available, rather than their precise locations and tracks (Commission for the Conservation of Antarctic Marine Living Resources, 2018). Automatic Identification System (AIS) data are also available for some regions and times. Vessels from nations outside of the Antarctic Treaty, CCAMLR, and IAATO are missing from the corresponding databases; however, it is unlikely that there are a substantial number of such ships. Most private yachts do not report either. An extrapolated number of 95 non-IAATO yachts compared to 18 IAATO-yachts⁸ entered Antarctic waters in the 2017/2018 austral summer.⁹

Antarctic tourism has increased since the 1950s (Enzenbacher, 1992). Cruise ships are present from October through March, peaking in January. While the number of operators, number of ships, number of voyages and number of passengers increased between 1992/1993 and 2018/2019, the number of operators and ships has leveled off; yet the number of voyages and passengers keeps rising (Bender et al., 2016; International Association of Antarctica Tour Operators [IAATO], 2018; **Figure 2**). Research vessels are present all year-round, peaking in January and February. The number of research vessels south of 60°S has doubled from about 12 in 2011/2012 to 25 in 2016/2017.¹⁰ The number of licensed fishing vessels (46 in 2017/2018), the number of licensing periods (52 in 2017/2018), and the number of licensed areas (119 in 2017/2018) have remained fairly constant

²COMNAP Antarctic Facilities Master List v 2.0.0, dated 08.12.2017; https://github.com/PolarGeospatialCenter/comnap-antarctic-facilities/raw/73f28e19f7e93f9e9e8b2c4dfb620b510e5eb256/dist/COMNAP_Antarctic_Facilities_Master.xls

³ATCM XLI, IP 71: IAATO Overview of Antarctic Tourism: 2017–2018 Season and Preliminary Estimates for 2018–2019 Season. Data from Appendix 1; <https://iaato.org/documents/10157/2398215/IAATO+overview/bc34db24-e1dc-4eab-997a-4401836b7033>

⁴CCAMLR List of authorized vessel for season 2017/2018; <https://www.ccamlr.org/en/compliance/list-authorized-vessels>

⁵Based on IAATO 2017 statistics: 2016–2017 Summary of Seaborne, Airborne and Land-Based Antarctic Tourism.

⁶Assuming 30 days/ship; CCAMLR List of authorized vessel for season 2016/2017; <https://www.ccamlr.org/en/compliance/list-authorized-vessels>

⁷Data provided by COMNAP based on COMNAP's Ship Position Reporting System (SPRS). Ships are requested to report once per day.

⁸ATCM XLI, IP 71: IAATO Overview of Antarctic Tourism: 2017–2018 Season and Preliminary Estimates for 2018–2019 Season. Data from Appendix 1.

⁹ATCM XXXIX, IP 36: Antarctic Tourism Study: Analysis and Enhancement of the Legal Framework, submitted by Germany. The German Environment Agency commissioned a study that showed, that of the >200 known yachts that sailed in the Antarctic Treaty area between 1997 and 2013, only 16% were IAATO-members at the time of their Antarctic Voyage.

¹⁰Data provided by COMNAP based on COMNAP's Ship Position Reporting System (SPRS).

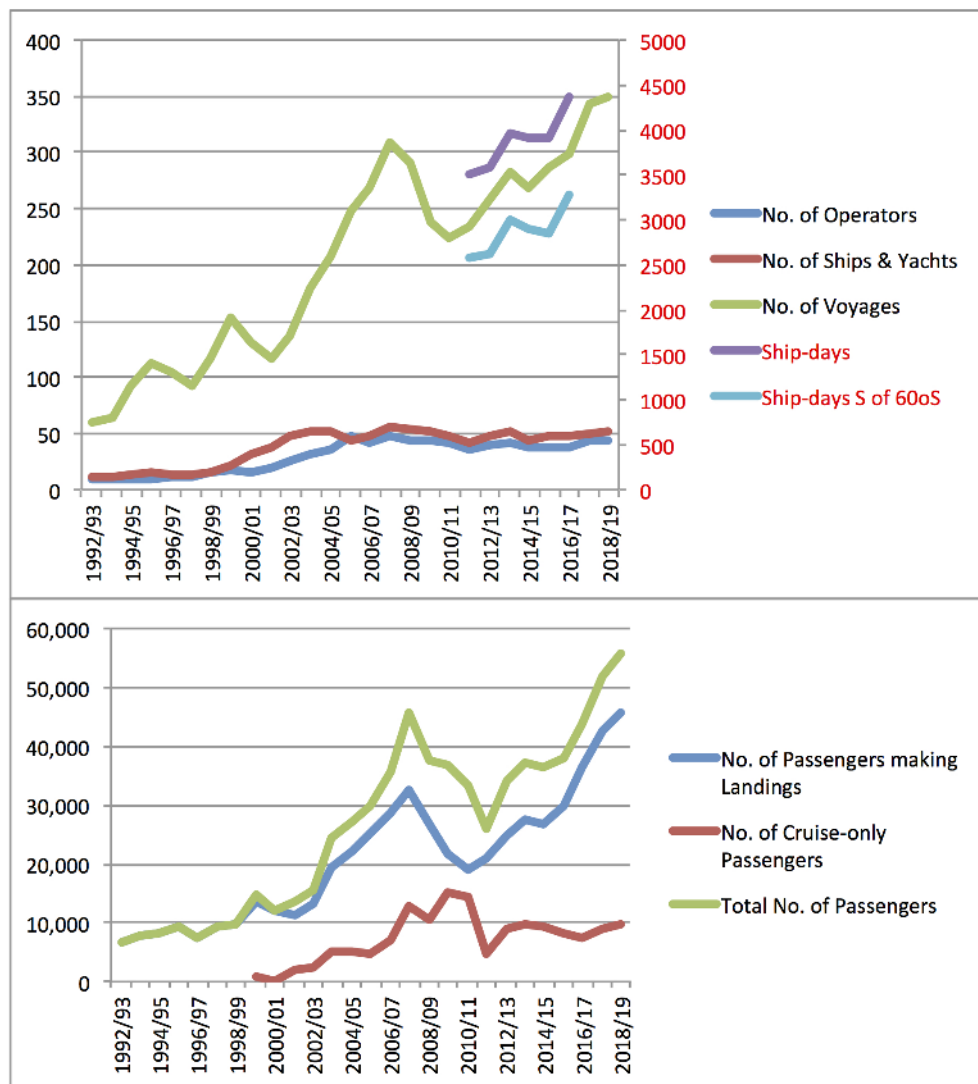


FIGURE 2 | Trends in Antarctic ship-based tourism. For more information on these data, see International Association of Antarctica Tour Operators [IAATO] (2018).

from 2011/2012 to 2017/2018¹¹. Ships are not evenly distributed. Rather, the Antarctic Peninsula and the Ross Sea experience the most ship traffic of all types.

Ship noise is continuous and consists of a broadband (10 Hz–20 kHz) cavitation spectrum overlain with distinct propeller and engine tones and harmonics (5–200 Hz) (e.g., Arveson and Vendittis, 2000; Kipple, 2002; Wales and Heitmeyer, 2002). In addition, icebreakers produce sounds related to pushing and crushing ice (Erbe and Farmer, 2000; Roth et al., 2013). Broadband radiated noise levels of large ships including icebreakers can be as high as 200 dB re 1 μPa m (Allen et al., 2012; Roth et al., 2013). Ships typically run echosounders for depth-ranging, and the ATCM has produced Resolution H (2014) “*Strengthening Cooperation in Hydrographic Surveying and Charting of Antarctic Waters*,” by which all ships of national

Antarctic programs (and all other ships) are encouraged to collect hydrographic and bathymetric data using powerful echosounders while in the Antarctic Treaty area. Such echosounders repeatedly (every few seconds) emit pings at multiple frequencies (typically above 10 kHz) with source levels up to 240 dB re 1 μPa peak-to-peak (pk-pk) and 200 dB re 1 $\mu\text{Pa}^2\text{m}^2\text{s}$ (Crocker and Fratantonio, 2016; Crocker et al., 2018).

Research in the Antarctic is carried out from ships, land-based platforms, and air. Research station and wharf construction may involve geotechnical work, rock breaking, and pile driving—all of which generate noise underwater (e.g., Soloway and Dahl, 2014; Erbe and McPherson, 2017). Driving piles into the seafloor with a vibrator creates underwater noise at 10–1000 Hz with distinct tonal structure and levels up to 170 dB re 1 μPa rms at close range (Dahl et al., 2015). Percussive pile driving creates impulsive underwater noise of up to 227 dB re 1 μPa pk-pk and 201 dB re 1 $\mu\text{Pa}^2\text{s}$ at close range (Hastings and Popper, 2005;

¹¹data from <https://www.ccamlr.org/en/compliance/list-authorized-vessels>

Illinworth and Rodkin Inc, 2007). Aircraft produce noise in air, however, noise transmits into water directly below (e.g., Erbe et al., 2017b, 2018b). Additionally, some countries, such as Germany, Italy, Spain, Poland, China, South Korea, and Russia, have been undertaking marine seismic surveys for research in the Antarctic (Breitzke, 2014). Germany alone acquired 59,621 km of multichannel seismic survey lines between 1976 and 2011 (Boebel et al., 2009; Breitzke, 2014). Seismic airgun arrays emit broadband (5 Hz–20 kHz) pulses repeatedly (every 5–20 s) at levels up to 224 dB re $1 \mu\text{Pa}^2\text{m}^2\text{s}$ (Ainslie et al., 2016; Li and Bayly, 2017).

Sound propagation in Antarctic waters differs from that at lower latitudes due to low surface temperatures and the possible presence of ice. In polar water, the sound speed increases with depth, which leads to upward refracting sound propagation paths and the establishment of a so-called surface duct. Sound trapped in the surface duct can travel over long ranges. Sound emitted near the surface will follow a refracted propagation path where it travels to some depth and then bends upward without interacting with the seafloor and thus without the associated reflection loss that occurs at the seafloor. Reflection occurs at the sea surface, and the associated loss depends on whether the surface is open or ice-covered, and on its roughness. First-year ice is typically smooth underwater and hence very little scattering loss occurs here, resulting in very effective sound propagation under such ice. Furthermore, given the deep bathymetry around Antarctica, there is no low-frequency mode stripping, meaning that low-frequency noise from ships or seismic airguns can travel over very long ranges (hundreds to thousands of kilometers; Siebert et al., 2014; Gavrilov, 2018). With such long-range propagation, the spectral and temporal features of sound change, because energy at different frequencies travels at slightly different speeds and along slightly different paths (termed “dispersion”; Horton Sr, 1974; Dushaw et al., 1993). Brief (100 ms), broadband (<20 kHz), high-amplitude pulses as emitted by seismic airguns turn into longer-duration (several seconds), narrower-band (<200 Hz), lower-amplitude, frequency-modulated sounds at distances of tens of kilometers (Yang, 1984; Siebert et al., 2014; Hastie et al., 2019). Such spectro-temporal changes in noise characteristics yield different types of noise impacts as a function of range.

NOISE IMPACTS

The effects of noise on marine mammals range from individual, short-term responses to population-level, long-term impacts (see Erbe et al., 2018a). In terms of severity, they also range from cases which might not result in any consequences, to those that prompt behavioral changes, mask communication, induce hearing loss, increase stress, or lead to death (e.g., in the case of tactical mid-frequency sonar affecting beaked whales; Fernández et al., 2013). Mortality can also occur in close proximity to underwater explosions (Ketten, 1995; Danil and St. Leger, 2011). These types of noise impacts have been reported not only for marine mammals but also for fishes and other taxa (e.g., Day et al., 2017, 2019; McCauley et al., 2017; Hawkins and Popper, 2018), which are preyed upon by marine mammals. Noise impacts on these taxa can thus indirectly affect marine mammals if noise leads to

a physical reduction in prey availability or to a change in prey behavior that affects its availability to predators. Examples for each type of effect of noise on Antarctic marine mammals or their closely related northern species are summarized in **Table 3**.

While the above impacts are experienced by individual animals, they can lead to population-level impacts. Animals might be displaced from preferred habitats into areas with higher predation risk, lower prey abundance, or poorer prey quality. They might suffer reduced energy intake while expending more energy. Malnutrition, stress and hearing loss might compromise health and lead to shortened life span. If enough individuals in a population are affected, then population dynamics may change. The Population Consequences of Acoustic Disturbance (PCAD) and Population Consequences of Disturbance (PCoD) models provide a conceptual framework that link short-term individual impacts to population consequences (National Research Council, 2005; Harwood et al., 2014; National Academies of Sciences, Engineering and Medicine, 2017). A well-studied example species is the elephant seal (both northern and southern), where disrupted foraging behavior due to noise leads to predictions of reduced foraging success in mothers; then a reduced maternal mass leads to reduced pup mass at weaning, which is predicted to negatively impact pup survival and lead to changes in population dynamics (New et al., 2014; Costa et al., 2016). Population consequences of disturbance can potentially be significant, in particular when noise-making activities occur in high-priority areas for a population.

Research on hearing abilities and the effects of noise on Antarctic marine mammals has been sparse and little data are available to assess the potential impacts of noise on their hearing. Out of the 23 marine mammal species that occur south of the Antarctic Convergence, a behavioral audiogram is only available for the killer whale (Branstetter et al., 2017), with some hearing information from auditory evoked potential measurements on a stranded long-finned pilot whale (Pacini et al., 2010). Behavioral audiograms remain the standard for hearing tests and provide a whole-animal response (including decision making by the animal); in contrast, auditory evoked potential audiograms reflect the averaged response of the auditory brainstem to acoustic stimuli only. The audiogram of the northern elephant seal could possibly be used as a surrogate for the southern elephant seal (Kastak and Schusterman, 1999). Although several anatomical predictions of the frequency range of hearing have been produced for mysticetes (Houser et al., 2001; Parks et al., 2007; Tubelli et al., 2012; Cranford and Krysl, 2015), no empirically measured audiogram exists for any mysticete species globally. Data on noise-induced hearing loss or impacts of stress in Antarctic marine mammals do not exist, although a fair amount of work has been performed on the endocrine response to stress in the southern elephant seal's close relative, the northern elephant seal (e.g., Ensminger et al., 2014; Jelincic et al., 2017). While the sounds made by Antarctic marine mammals have been documented (e.g., Erbe et al., 2017a), there is no information (such as critical ratios) to assess masking of those sounds by noise, except for four studies indicating anti-masking processes in humpback, killer, and long-finned pilot whales elsewhere (see Erbe et al., 2016). There have been no dedicated studies on

TABLE 3 | Examples of reported effects of noise on Antarctic marine mammals (* or closely related species).

Noise source	Species	Effect of exposure	References
Shipping	North Atlantic whale*	Increased stress levels	Rolland et al., 2012
Shipping	Humpback whales	Effects on foraging, including slower descent rates and fewer side-roll feeding events per dive	Blair et al., 2016
Shipping	Killer whales	Noise source avoidance, predicted masking of communication sounds	Erbe, 2002
Seismic airguns	Sperm whales	Disruption of foraging, decreased adult and infant mass, decreased infant survival, predicted population level effect	Farmer et al., 2018
Seismic airguns	Fin whales	Song modifications, sound source avoidance	Castellote et al., 2012
Pile driving	Harbor seals*	Noise source avoidance, predicted effect on hearing threshold	Hastie et al., 2015; Russell et al., 2016
Shipping, naval sonar	Blue whales	Changes in call rate	Melcon et al., 2012
Naval sonar	Blue whales	Disruption of foraging	Goldbogen et al., 2013; Southall et al., 2019a
Naval sonar	Northern bottlenose whales*, Baird's beaked whales*	Avoidance, interruption of foraging	Stimpert et al., 2014; Miller et al., 2015
Naval sonar	Minke whales	Avoidance responses over large distances.	Kvadsheim et al., 2017
Naval sonar	Sperm whales	Switch to a non-foraging, non-resting state. Reduction of time spent in foraging states and reduced probability of prey capture attempts.	Isojunno et al., 2016
Scientific echosounders	Beaked whales (<i>Ziphius</i> and <i>Mesoplodon</i> species)	Interruption of foraging or vessel avoidance. Reduced acoustic activity when echo-sounders were actively transmitting. When echo-sounders were in passive mode, the detection rate showed a 20-fold increase.	Cholewiak et al., 2017
Acoustic deterrent devices	Killer whales	Habitat exclusion	Morton and Symonds, 2002

the behavioral responses of marine mammals to noise in the Antarctic, though some studies have been undertaken on the same species in other regions (Table 2). It is uncertain how results from other regions (where animals potentially undergo different life functions; e.g., feeding in the Southern Ocean versus breeding at low latitudes) and other populations or species relate to Antarctic marine mammals, especially in light of the modulating influence that behavioral and exposure context can have on reactions to noise (Harris et al., 2018).

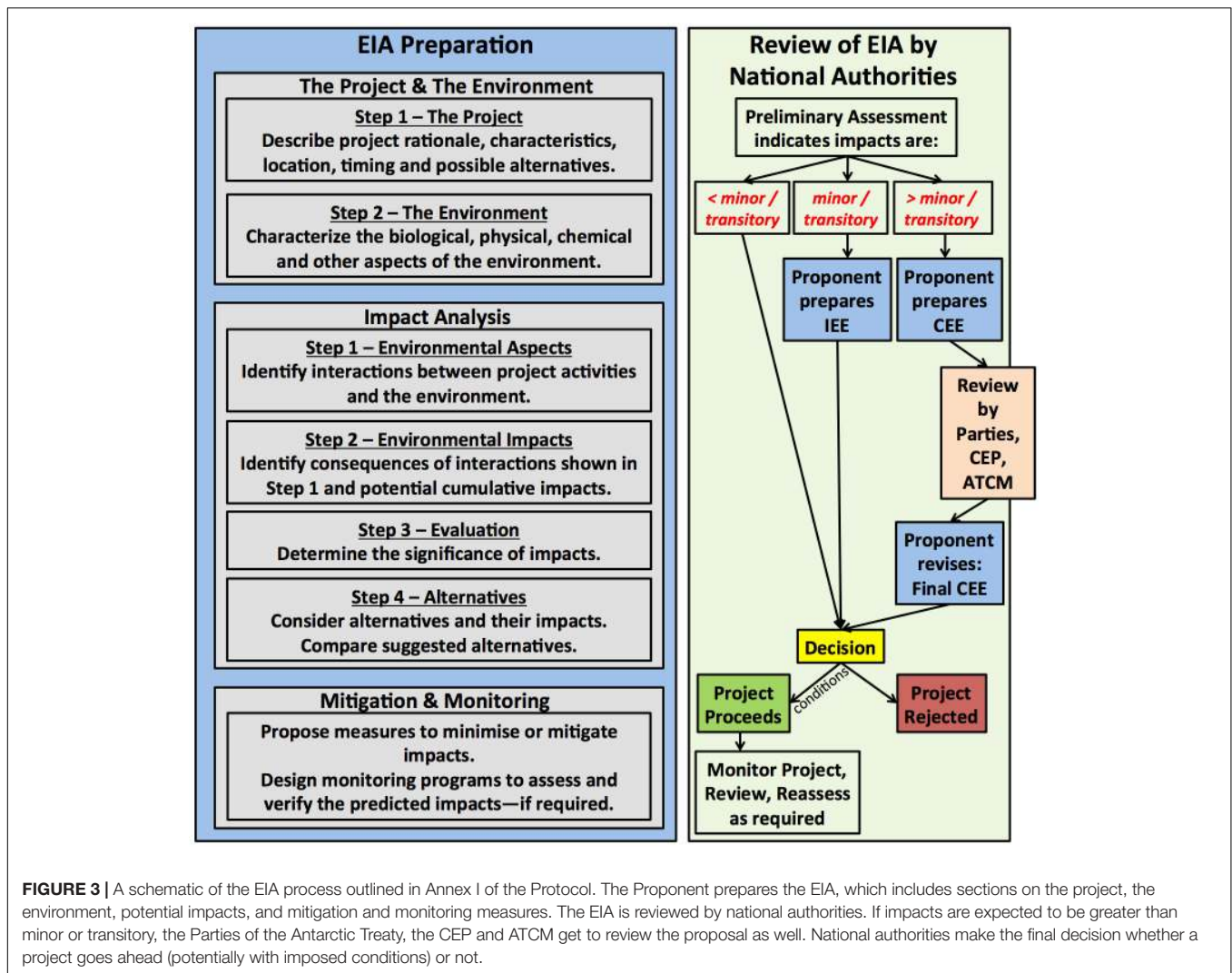
NOISE MANAGEMENT

Annex I to the Protocol and the Guidelines for Environmental Impact Assessment in Antarctica (Resolution 1, 2016) outline the Environmental Impact Assessment (EIA) process for activities in the Antarctic. The proponent prepares the EIA document, which describes the project and the environment, identifies potential interactions and consequences, determines the significance of predicted impacts, considers alternatives, and designs mitigation and monitoring programs (Figure 3). Monitoring is (a) required for activities expected to have more than a minor or transitory impact, (b) suggested for those of minor or transitory impacts, and (c) not required for those of less than minor or transitory impacts. The EIA is reviewed and assessed by national authorities. Projects with environmental impacts that are less than minor or transitory are allowed to proceed—potentially with conditions imposed. Projects with environmental impacts that are minor or transitory require that the proponent prepare an Initial

Environmental Evaluation (IEE). Projects with environmental impacts that are more than minor or transitory require that the proponent prepare a Comprehensive Environmental Evaluation (CEE). The CEE is reviewed by all the Antarctic Treaty Parties, by the CEP, and at the ATCM. The final CEE addresses comments from this review process. The national authorities eventually make a decision to either reject the project or allow the project to proceed—likely with conditions imposed.

Since the EIA process is conducted at a national level, several countries and jurisdictions have developed guidelines and regulations for the management of underwater noise (Erbe, 2013; Lucke et al., 2016). Typically these involve exposure modeling and impact prediction, mitigation, and sometimes *in situ* monitoring related to intense sources such as seismic airguns or pile driving.

Impact prediction requires knowledge of sound characteristics and levels at which different types of impact occur. While the regulations in different countries often aim to protect the same or similar species from the same types of impact, the metrics, thresholds, and management procedures that are applied differ. One reason for these differences is that the impact of sound on marine mammals is an active field of science, and new knowledge is being delivered gradually. There is a general acceptance that hearing damage can result from either an instantaneous exposure to very high sound pressure levels or from the accumulated exposure to acoustic energy over an extended period of time. This requires management with dual criteria and thresholds to address the different types of sound sources in the ocean, one sound pressure based, the other energy



based (Southall et al., 2019b). Regulators aim to ensure that any exceedance of these thresholds does not have significant impacts to the noise-exposed populations. Energy-based criteria present particular practical challenges in that the animals' behavior, and in particular how they move in three dimensions with respect to a sound source, affects the received acoustic exposure. Often this is the least known and most uncertain component of a risk assessment.

For example, for high-frequency cetaceans such as porpoises and exposure from impulsive noise such as impact pile driving, the United States uses a dual criterion (i.e., applies the one resulting in the largest effect distance) of 196 dB re 1 μ Pa zero-to-peak pressure and 140 dB re 1 μ Pa²s cumulative sound exposure (weighted and integrated over 24 h) as the onset of temporary threshold shift (TTS), and a dual criterion of 202 dB re 1 μ Pa zero-to-peak pressure and 155 dB re 1 μ Pa²s cumulative sound exposure (weighted and integrated over 24 h) as the onset of permanent threshold shift (PTS) (National Marine Fisheries Service, 2018). Germany applies a dual criterion of an unweighted single-impulse (i.e., not cumulative) sound exposure

level of 160 dB re 1 μ Pa²s and 190 dB re 1 μ Pa peak-to-peak pressure at a range of 750 m from the pile in order to avoid TTS (Bundesministerium für Umwelt Naturschutz und Reaktorsicherheit, 2014). While the United States criteria are applied at the receiving animal, which can be anywhere around the source, the German criteria are referenced to the exact distance of 750 m from the source.

The criteria employed by the two countries are difficult to compare, and it is not possible to generalize which country uses stricter regulations, because the criteria apply at different ranges, and the site-specific sound propagation environment will affect at what range certain levels are exceeded. Furthermore, Germany uses unweighted sound exposure, while the United States weights exposures according to categorization to a defined functional hearing group. Germany uses single exposures, while the United States integrates over 24 h. Different regulators also vary in the degree of precaution they are minded to apply, given the high levels of uncertainty in so many aspects of this topic. Germany, for example, considers TTS as the beginning of injury, whereas the United States only considers the onset of

PTS auditory injury under the Marine Mammal Protection Act (MMPA) (National Marine Fisheries Service, 2016).

There are a number of mitigation procedures that can be applied to reduce noise exposures from various sources (Weir and Dolman, 2007; Dolman et al., 2009; Merck et al., 2014; Verfuss et al., 2016). Some methods can be applied at or close to the source. This might involve using a quieter source or one that produces a different type of signal that might reduce specific impacts (e.g., marine vibroseis versus seismic airguns; Duncan et al., 2017). Sound barriers (e.g., bubble curtains) may be installed near a fixed source to reduce sound propagation into the wider environment. Operations might be scheduled to occur at times when marine mammal abundance is expected to be lower or to avoid times of particular vulnerability, such as calving seasons (Van Opzeeland and Boebel, 2018). During operations, safety zones might be searched for marine mammals (e.g., using visual, infrared, and/or passive acoustic methods). A delay in initiating activities or a shut-down might result if animals are detected within mitigation zones. The effectiveness of this as a mitigation approach depends on the ability to detect animals and in many cases results in little reduction of risk (Leaper et al., 2015).

Mitigation effectiveness and practicality depend on the activities to be mitigated, the environment, the target species, and the approach taken. Multiple mitigation approaches are sometimes applied. Generally, mitigation can reduce the risks to marine mammals, but not eliminate them. Impacts such as behavioral disturbance and masking are particularly difficult to minimize except by reducing sound at the source. In the presence of knowledge gaps and uncertainty on noise impacts, regulators are expected to take a conservative approach, following the precautionary principle. What level of mitigation is reasonably practicable is debatable amongst proponents and regulators.

INTERNATIONAL RESPONSIBILITY

Concern about the effects of anthropogenic underwater noise on marine life is widespread and increasing (as evidenced by, e.g., publication patterns; Williams et al., 2015; Shannon et al., 2016). In some countries, underwater noise is considered a form of water pollution, alongside chemical pollution (e.g., in the European Union; van der Graaf et al., 2012). Sound underwater travels much faster and farther than it does in air. Depending on the sound propagation conditions, sound can travel hundreds of kilometers and traverse entire ocean basins. Noise therefore crosses legal boundaries and the noise received in one jurisdiction might originate in a region that is under different jurisdiction, making noise regulation and ultimately conservation management an international responsibility.

The Convention on Environmental Impact Assessment in a Transboundary Context (Espoo Convention, United Nations Economic Commission for Europe [UNECE], 1991) requires that member states undertake environmental impact assessments of planned activities, and then inform and consult other member states if the impacts are expected to occur in other states as well. There are several examples where countries that border

the same body of water have reached international agreements to manage noise and other stressors. This is the case for some European seas (Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area - ACCOBAMS; Pavan, 2006; Authier et al., 2017), Baltic (Helsinki Commission - HELCOM; Backer et al., 2010), European Union (Marine Strategy Framework Directive - MSFD; van der Graaf et al., 2012), and other regions.

Other international organizations that recognize underwater noise as a threat to marine mammals (including in the Antarctic) are the IWC, the Convention on Biological Diversity (CBD), the Convention on Migratory Species (CMS), the International Maritime Organization (IMO), and the United Nations General Assembly. Anthropogenic underwater noise was the focus topic for the UN Informal Consultative Process on Oceans and the Law of the Sea in June 2018¹².

The IWC supported a workshop on global soundscape mapping in 2014 and a workshop on acoustic masking in 2016, and continues to discuss underwater noise at annual meetings of its Scientific Committee. In 2018, the IWC passed a Resolution on Anthropogenic Underwater Noise¹³ by consensus, recognizing that chronic anthropogenic underwater noise is affecting the marine acoustic environment in many regions, and that there is emerging evidence that compromised acoustic habitat may adversely affect some cetacean populations.

In 2014, the Conference of the Parties to the CBD (Decision XII/23) encouraged parties to take appropriate measures to avoid, minimize, and mitigate the potential significant adverse impacts of anthropogenic underwater sound on marine and coastal biodiversity. It also encouraged governments to require environmental impact assessments (EIAs) for sound-generating offshore activities, and to combine mapping of the acoustic footprints of activities with habitat mapping to identify areas of risk.

The Conference of the Parties to the CMS adopted a Resolution on “Adverse impacts of anthropogenic noise on cetaceans and other migratory species” in 2017, which urges parties, whose flagged vessels travel beyond national jurisdictional limits, to undertake EIAs and manage the impact of anthropogenic noise on CMS-listed marine species and their prey. Guidelines for EIAs of underwater noise were also published in 2017 under this Convention.

The IMO stated that uncertainty as to the effects of noise should not preclude efforts toward developing quieting technologies for commercial ships (International Maritime Organization, 2009). The IMO developed guidelines on underwater noise reduction (MEPC.1/Circ.833) in 2014 acknowledging that noise from commercial ships may have both short- and long-term negative consequences on marine life. The International Convention for the Prevention of Pollution from Ships (MARPOL 1973/1978) and the International Code for Ships Operating in Polar Waters (Polar Code) were both developed by the IMO and have implications for ship noise in the

¹²http://www.un.org/depts/los/consultative_process/ICP-19_information_for_participants.pdf

¹³https://iwc.int/document_3685.download

Antarctic. MARPOL bans heavy fuel oil, both as fuel and cargo, from south of 60°S, thus limiting older vessels, which may emit more noise due to older, less efficient propulsion and design. The Polar Code requires that vessel masters consider marine mammal aggregation and migration areas when planning routes.

The International Association of Antarctic Tour Operators (IAATO) promotes environmentally responsible travel to Antarctica and could be an organization to also address underwater noise. However, some commercial operators are not members of the IAATO.

The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has the objective of conserving Antarctic marine life and focuses on commercial fisheries species (e.g., krill and toothfish). Impacts of anthropogenic noise on marine mammal prey species may thus need to be considered by CCAMLR.

RESEARCH AND MANAGEMENT NEEDS

In November 2018, we held an international workshop on the possible effects of noise on Antarctic marine mammals in Berlin, Germany. Twenty-nine workshop participants (15 biological scientists, 5 regulators, and 9 Antarctic seismic and ship noise producers) were asked what they saw as key research and management needs for this topic in the Antarctic. We then asked all participants to rate the importance of each topic on a scale from 1 (low importance) to 5 (high importance). The complete list of topics and their scores can be found in the **Supplementary Material**. The research needs that received the highest rankings by workshop participants were (1) better data on abundance and distribution of Antarctic marine mammals with particular urgency to identify areas of high abundance (“hotspots”) and low abundance (“coldspots”), (2) hearing data for Antarctic marine mammals, in particular a mysticete audiogram, and (3) an assessment of the effectiveness of various noise mitigation options.

Management needs with the three highest scores overall were a refinement of noise exposure criteria, clear application guidance for environmental impact assessments, and transparency in regulatory decisions. Transparency was the highest-ranking need for proponents (4.67/5), though ranked lower by regulators (3.25/5). Regulators ranked the refinement of noise exposure criteria highest (4.5/5) and proponents agreed this was important (4.17/5). Biological scientists prioritized the need for agencies with an Antarctic interest (e.g., SCAR and CCAMLR) to join forces on noise management (4.4/5), establishing a public database on marine mammal distribution (4.2/5) and the sharing of research and ancillary data amongst users (e.g., of seismic data and echosounders data) (4.1/5). There were a few very specific research needs that directly relate to management and regulation requirements, such as (1) the allowance of hearing impairment recovery in cumulative exposure calculations, (2) justification and modification of the 24 h integration period for cumulative exposure calculations, and (3) choosing an appropriate metric and weighting to predict behavioral disturbance. These three needs and studies on responses to natural ambient noise were

ranked of very high importance by potential noise producers, yet low by regulators.

Assessing and managing underwater noise and its potential impacts on marine mammals in the Antarctic is complex and difficult. Multiple countries operate in Antarctica, and many stakeholders and sectors have an interest in the Antarctic (tourism, fisheries, shipping, research, and conservation). In addition to the complicated management framework, there are significant scientific knowledge gaps. Antarctic species are understudied. Some undergo critical life functions while in the Antarctic (such as feeding by mysticetes before migration to breeding grounds at lower latitudes) and it can only be speculated how impacts potentially incurred in the Antarctic will affect the fitness of these animals when in other areas. Applying data on noise impacts from other areas or species should be avoided until similarities are proven. The unique aspects of the Southern Ocean (i.e., the species and their life functions in this environment, the ambient noise, and the sound propagation characteristics) constitute a critical need for research on the effects of anthropogenic noise.

Many of the research needs we present here have been internationally recognized and some are at least partially addressed by other entities. For example, the urgent need to identify marine mammal hotspots has also recently (October 2018) been recognized by the IUCN Marine Mammal Protected Areas Task Force, proposing 15 candidate Important Marine Mammal Areas (IMMAs) for the Southern Ocean and Sub-Antarctic Islands¹⁴. The Subcommittee on Ocean Science and Technology (SOST), which is a partnership between the United States Office of Naval Research, Chief of Naval Operations N45, the Bureau of Ocean Energy Management, the National Oceanic and Atmospheric Administration, and the Marine Mammal Commission, called for proposals for mysticete audiograms in mid-2018. The Joint Industry Program of Oil and Gas Producers currently include a study on masking in marine mammals. Some research needs, such as the effectiveness of certain mitigation methods, behavioral responses, and prey responses (e.g., availability of krill), could potentially be developed as proposals for future voyages to Antarctica.

Data sharing is one aspect of international collaboration and efforts are underway to make seismic and hydrographic data publicly available. There appear to be significant delays of several years in this process, but the complexity, effort, and costs of data preparation, warehousing, and support are considerable.

It is encouraging that the international scientific community is coming together to review current knowledge as reported here and that efforts are underway to fill some of the research gaps that we recognized. The Antarctic is unusual in its sound transmission characteristics, its species community, and the way in which humans use its waters. Not all findings from other areas of the world are necessarily applicable to this environment, and

¹⁴<https://www.iucn.org/news/marine-and-polar/201810/fourth-important-marine-mammal-areas-workshop-adds-15-candidate-immas-southern-ocean-and-sub-antarctic-islands>

studies addressing the effects of noise specifically in the Antarctic are often lacking. Furthermore, different nations operate around the continent without necessarily coordinating their efforts. The effects of multiple stressors and multiple sound sources have been recognized as a high research priority in the marine science community in general (Rudd, 2014). In the Arctic, an integrated approach in the management of noise sources has been called for Moore et al. (2012). A similar approach would be prudent in the Antarctic. In 2048, the Protocol on Environmental Protection of the Antarctic Treaty may be reviewed if one of the Parties requests it. Additional anthropogenic activities such as mining may be considered. Such activities would lead to an increase of noise in the Antarctic. We hope that our review here will contribute to identifying and steering where research and management actions are most needed to protect the Antarctic environment from anthropogenic noise as much as possible.

AUTHOR CONTRIBUTIONS

All of the authors participated in the workshop on Antarctic noise and effects on marine mammals, collaborated on the data gap table, and wrote sections of the report and/or manuscript. At the workshop, the following authors reviewed, summarized and presented the main topics. HH and AS-S: regulation. MM: human

activities in Antarctica. MD: Antarctic marine mammal ecology. DH: hearing and hearing impairment. CE: acoustic masking. SK: behavior. JO: population consequences. RM: marine mammal prey impacts. JG: mitigation and monitoring. MS: ambient noise and propagation. MM, AM, and CE drew the figures. CE and VJ organized the workshop and produced the first draft of the overall manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2019.00647/full#supplementary-material>

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Conflict of Interest: MS was employed by company DW-ShipConsult.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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