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Risks posed to the Antarctic marine environment by acoustic instruments: a structured analysis

SCAR ACTION GROUP ON THE IMPACTS OF ACOUSTIC TECHNOLOGY ON THE ANTARCTIC MARINE ENVIRONMENT

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Abstract: The risks posed by a range of acoustic scientific instruments were assessed by the construction of matrices of scale and likelihood. We recognized six levels of impact ranging from none or short term, minimal behavioural response (Level 1) to multiple injuries and fatalities and/or compromised populations (Level 6) and six levels of likelihood ranging from "Expected in almost all instances" (Level 1) to "cannot see how it could happen" (Level 6). Typical scientific instruments ranging from acoustic releases to large air gun arrays were assessed. To provide a perspective for the risks of scientific operations, other activities were also ranked. These included large chemical explosions, submarine detection sonars implicated in some mass strandings of cetaceans and normal Antarctic shipping activities. The conclusion reached was that most scientific instruments pose a similar or lower risk than normal shipping operations. High source-level equipment poses some risk to individual animals' hearing and so should be mitigated. Likewise, survey planning should be designed to avoid trapping animals in narrow, constricted sea ways. Long term, cumulative impacts are still difficult to detect in areas with greater anthropogenic noise than the Antarctic but we concluded that any possible long term impacts should be mitigated by maintaining the low levels of activity using high source-level equipment through data sharing and survey planning.

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Introduction

The impact of anthropogenic noise on the marine environment is being addressed in many fora around the world, ranging from scientific workshops and symposia to legal proceedings and the mass media. The issue is a difficult one to address because rigorously controlled observations are hard to acquire and solid evidence circulates with anecdotes, opinion and rumour. It is also difficult to evaluate the absence of evidence. For every well documented case of harm probably associated with acoustic technology, there are many surveys for which there is no evidence of an adverse impact. Is this because we simply are not detecting or even looking for the impact or is it because the harmful surveys are rare events? The problem has been further compounded by the broad, multi-disciplinary knowledge needed to understand the issues. An understanding of animal hearing and biology, marine acoustics and acoustic engineering all impinge on the assessment of risks posed by human activity. In the Antarctic, the types and intensity of human activity are very different to other, more heavily populated areas.

Another question that is seldom asked in discussions on the impact of anthropogenic noise is: How do the risks posed by the scientific use of sound compare to the effect of other activities such as fishing and shipping? Such a question is important because it should focus regulation and mitigation effort on the largest threats as a high priority.

The SCAR Action Group on the impacts of Acoustic Technology on the Antarctic Marine Environment met first in 2001 and produced a report (SCAR 2002) that tried to summarize the issues that need to be considered in assessing the impacts of the use of anthropogenic sound in the Antarctic. Considerable effort was devoted to the range of equipment likely to be used in the Antarctic because we wished to assist regulators who must decide if a particular survey is a threat to the environment. The report also focussed squarely on the Antarctic environment. The risks to a remote area such as Prydz Bay that may be visited by 3–4 vessels per year are clearly different to high traffic areas such as the Gulf of St Lawrence or areas of intense seismic exploration such as the northern Gulf of Mexico.

The first workshop identified that there was a continuum of risk from acoustic technology, ranging from benign to potentially severe; but it lacked a conceptual framework with which it could get a clear picture of how different technology should be regarded. Since then, we became aware of several approaches that allow ranking of the risks and clearer expression of the potential impacts and their

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likelihood. The field is still fraught with uncertainty but structured risk analysis can provide a way forward for discussion of the possible impacts and provide an understanding of costs and benefits in assessing surveys. A qualitative risk analysis of a range of acoustic technology was undertaken at a second workshop held in Cambridge, UK, in May 2004. The qualitative methods used also provide a way of ranking risks for individual programs to make judgments on what is acceptable and what is not, in the absence of definitive research. This paper is one of the results of the second workshop.

Risk analysis method

This risk analysis is offered as a guide to the management of scientific surveys with the aim of identifying surveys that require more attention to minimising impacts. It starts from the perspective of a regulator faced with the question: "What are the risks of this proposed survey?

For most parts of the world, the discussion has been on how to regulate and mitigate industry seismic and high powered military sonar. In Antarctica, the discussion has covered the full range of acoustic equipment. Hence, the approach used here starts with the equipment typically deployed in scientific surveys. Risk analysis that starts from the biological end is also valid and necessary to inform the analysis of equipment. Some of this was attempted in a less structured way at the first SCAR workshop but at the second workshop, it was decided to concentrate on the risks posed by the technology. The different risk matrices have been constructed for typical instruments in use in marine science. The large airgun array assessed, which is based on one deployed by a US research institution, is somewhat atypical because it has a larger volume than most arrays, even those in use by industry. It was assessed because output data were readily available and it represents an extreme example. To provide some perspective on the risks of scientific equipment, further matrices have been constructed for shipping, for the military sonar implicated in some whale mass strandings and for chemical explosives used for seismic refraction; a method employed in the past and no longer in use because of technical, environmental and safety issues.

The method is based on a standard technique employed in many fields around the world. It is set out in the Australian and New Zealand Standards Association Risk Management report (Standards Association of Australia 1999). The system is simple and qualitative but has the advantage that no specialized risk analysis training is necessary follow the process. Also, more quantitative approaches are not possible at present. The method was modified from the standard by not using single word descriptors of 'Impact' or 'Likelihood' to avoid arguments over semantics. Some matrices distinguish between the risk to individual animals and populations where the SCAR group felt they were different.

There are more sophisticated approaches possible, however, they require statistical detail for a specific activity in a specific place. The group had access to some detailed calculations of instrument outputs and 'footprints' to compare with Temporary Threshold Shift measurements for marine mammals (Finneran *et al.* 2000, 2002, 2003) to aid the risk estimates however the main source of information was the research experience within the SCAR Action group and knowledge of the literature.

In arriving at a ranking, the group considered what the ranking for the most sensitive Antarctic species would be. The result might be different for critically endangered species in other regions such as the breeding grounds of the Northern Right whale. Because the process looked at generalised activities, risks could increase for biological "hot spots", or narrow sea ways. Assessment of long term cumulative risk will be discussed after the presentation of the risk matrices.

Risk matrix construction

The risk matrix is constructed using qualitative descriptions of impact or consequence versus qualitative description of likelihood. The key issues are the detailed description of the levels in each matrix and the number of levels.

Consequences (Table I)

In defining consequences or impacts, we define injuries as including auditory damage and reduced hearing sensitivity

Table I. Consequences or impacts of an activity. Not all impacts listed in a level are necessary to receive the rating. For example, Long term displacement (months) of much of a population would produce a ranking of 5 even if there were no injuries of fatalities.

Level	Detailed description
1	Individuals show no response, or only a temporary (minutes) behaviour change. No change to environment or populations.
2	Individuals show short term (hours) behaviour change. Temporary displacement of a small proportion of a population; small proportion of habitat affected; no impact on ecosystem function.
3	Longer term (days) simultaneous displacement of a higher proportion of a population; disruption to behaviour; interference with feeding.
4	Simultaneous displacement and disruption over a period of weeks to behaviour and feeding of a large part of a population, a few injuries, some interference with breeding success
5	Long term displacement (months) of much of a population, injuries common, substantial interference in a season's breeding success, fatalities rare
6	Injuries very common, fatalities, population jeopardised, long term displacement from large or important area

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Table II. Likelihoods for single surveys. This list of likelihoods differs from that used in the Australian Standard by the addition of Level F - Cannot see how it could happen. This list refers to single surveys. Questions of cumulative impacts were not addressed in this ranking exercise.

Level	Description
A	Expected in almost all instances
B	Will probably occur in most cases
C	Could occur in some cases
D	Could occur in a few cases
E	May occur in exceptional circumstances
F	Cannot see how it could happen

as well as other trauma, such as decompression effects caused by behavioural change. Only one of the impacts listed is necessary to be classified at a level. Where injury is possible for individuals but the Action Group thought that the risks to populations was lower, the risks are separated with risk to individual shown by an I in the matrix with P indicating the risk for populations. This approach is appropriate for the Antarctic. It would not apply to such an endangered species as the Northern Right whale where numbers are so low, injury to individuals has a severe consequence for the entire population.

Likelihood (Table II)

The likelihood is based on what is known about the equipment, experience with the marine environment and knowledge of the most sensitive species. For the more severe consequences, we have tried to ask the question; "How could you produce such a result with such equipment?" For example: How could you produce a Levels 4 to 6 effect with an acoustic release? If the group could not think of any way of producing the impact, it was listed Likelihood F. This is not to say that the likelihood is zero, although for some equipment it may be vanishingly small, or that further evidence may demonstrate an impact. This approach is directed at individual surveys in Antarctic waters. Issues of long term and cumulative effects will be discussed separately.

The Consequence levels contain a mixture of both population effects and individual effects. The production of any one effect was sufficient to achieve a ranking. For example, the SCAR working group regarded rare fatalities as deserving a Level 5 rank even though it may have no population level impact. Likewise, even if there were no fatalities, long term displacement was considered sufficiently undesirable to be Level 5.

Standards Association of Australia (1999) recommend the use of a final matrix that ranks risks as high, moderate or low. The workshop participants decided not to take this final step because it includes a value judgement about what levels of risk are low to high. This will ultimately be decided by individual regulators what constitutes an acceptable risk, particularly in relation to the benefits of an activity.

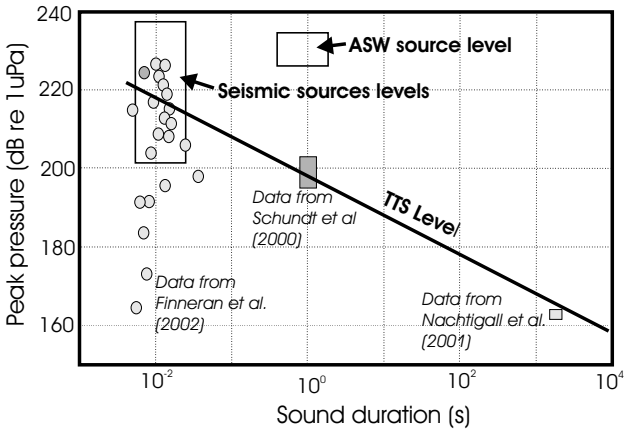


Fig. 1. Temporary Threshold Shifts in marine mammal (Finneran *et al.* 2002). Sounds above the TTS line are expected to produce TTS. TTS results from a combination of sound peak pressure and duration. Vertical axis is peak received pressure. White rectangles indicate the range of source levels for seismic surveys and for published information on larger submarine detection sonars (ASW).

Source levels and Temporary Threshold Shifts in marine mammals

The understanding of the possible impacts of anthropogenic noise on the marine environment and on the auditory mechanism of marine mammals in particular has been improved by experimental work on captive animals. A focus has been on the sound levels needed to produce Temporary Threshold Shift (TTS) in marine mammal hearing. TTS is the condition of reduced sensitivity of hearing produced by loud noise. It is reversible but if it is repeated persistently, the cumulative effect can lead to Permanent Threshold Shift (PTS) or, in the extreme, deafness. Knowing the levels at which TTS starts allows an understanding of what sound pressure levels represent the start of potential hearing damage and allows a precautionary limit to be defined for sound exposure. The scarcity of such knowledge has been a major problem for assessing the impacts of anthropogenic noise (Richardson *et al.* 1995).

A body of data allowed Finneran *et al.* (2002) to plot the sound intensity versus duration needed to produce TTS in marine mammals (Fig. 1). The form of the relationship is very similar to the relationships worked out for terrestrial animals so the group felt confident it could be used to predict TTS criteria for marine mammals not tested. The basic relationship is that increased energy is the cause of TTS expressed as sound intensity by duration. A doubling of sound duration causes a reduction of 3 dB in the level at which TTS occurs.

The implications for understanding the risks posed by

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scientific instruments is that it is possible to estimate the amount of exposure needed to produce TTS based on the sound level and the duration of exposure. For example, if an instrument produces pulses of 200 dB re 1 µPa of 1 ms duration, an animal would need to receive around 1000 pulses to suffer TTS, provided there was insufficient time between pulses to allow the ear to recover. This allows realistic calculations of the area of influence of both an individual instrument and of an overall survey activity, providing a firmer basis for estimating risk of TTS and the start of potential hearing degradation.

The length of sound pulses also influences the degree of disturbance by the sound. Mammalian nervous systems require approximately 200 ms to process the "loudness" of a sound (R. MaCauley, personal communication 2003). Therefore, sounds of shorter duration will not be perceived as being as loud as longer pulses. This may explain the occasional observations of cetaceans approaching loud sources such as airgun arrays. The animals may not be perceiving the true "loudness" of the source while experiencing adverse effects. At greater distances, the short pulses of scientific equipment may produce less behavioural response in animals than the long pulses produced by some military sonars. The conclusion from these considerations is that high source level and long pulse length increase the impact of sounds.

Impacts on deep-diving animals

Examination of animals, beaked whales in particular, stranded in events associated with Antisubmarine Warfare exercises and further studies of deep-diving cetacean carcases have discovered emboli in fatty tissues and other fluids (Jepson *et al.* 2003, Piantadosi & Thalman 2004, Fernández *et al.* 2004). An analogy has been drawn with symptoms of decompression sickness in humans (Jepson *et al.* 2003). The possible causes of these effects are not known but three mechanisms have been suggested (P. Tyack and D. Wartzok, personal communication 2004):

1. Formation of bubbles caused by exposure to high intensity sound (Crum & Mayo 1996).
2. Extreme stress response by the animals to the sound of the sounders involved.
3. Modification to diving behaviour producing decompression effects. The small amount of information on beaked whale diving behaviour indicates that the whales tend to spend very small amounts of time in the top 10 m of the water column (P. Tyack, personal communication 2004). This behaviour allows a form of saturation diving to depths of around 1000 m to feed. Loud or alarming sound could cause the animal to stay in the sound shadow at the surface longer than normal, causing decompression effects.

Table III. Consequences vs likelihood matrix for an acoustic release.

	Consequences					
Likelihood	1.	2.	3.	4.	5.	6.
A	X					
B						
C						
D						
E		X				
F			X	X	X	X

The first mechanism seems less likely than the other two because, in some stranding events, the animals could not have been subjected to the sound pressure levels though to produce bubble formation, although this mechanism is not well understood. The second and third mechanisms are similar and may relate to high received levels of sound, sensitivity to the frequency content or even the shape of the sound pulse. Experiments aimed at developing devices that warn whales of approaching ships suggest that some swept frequency pulses may be particularly irritating to Right whales, even at low sound levels (P. Tyack, personal communication 2004).

Risk evaluation

Acoustic release

Acoustic releases are devices that detach instruments from moorings in deep water when they receive acoustic signals from the surface. Typically, the release has a receiver but also transmits sound pulses so the approaching vessel can locate the mooring.

This matrix (Table III) was constructed for a typical acoustic release listed on a commercial web site. Output pings range from 7.5–50 kHz, and source levels from 185–190 dB re 1 µPa @ 1m. Acoustic release beams are omnidirectional. Pings are of millisecond length repeated over about 15 minutes during recovery**.** Acoustic releases are located and released using a sequence of pings that might displace one or two animals in unusual circumstances.

Bathymetric echo sounder

This matrix (Table IV) is based on a single beam echo

Table IV. Consequences/Likelihood matrix for a 12 kHz bathymetric echo sounder.

	Consequences					
Likelihood	1.	2.	3.	4.	5.	6.
A	X					
B						
C						
D		X				
E			X			
F				X	X	X

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Table V. Consequences/Likelihood matrix for an array of single beam echo sounders used for fisheries research.

	Consequences					
Likelihood	1.	2.	3.	4.	5.	6.
A	X					
B						
C						
D		X				
E			X			
F				X	X	X

sounder commonly used for collecting bathymetric data. The echo sounder has a frequency of 12 kHz, source level of 232 dB re 1 μPa @ 1m, and typical pulse lengths of around 1 ms. Main beam is aimed vertically below the ship, and has around 10 degree beam width.

Calculations of the volume affected by the echo sounder and comparisons between its outputs and TTS data indicate that the chance of TTS is only in a small volume immediately under the tranducers, making Level 4 and above impacts Inconceivable to the workshop. Some minor displacement of animals in the immediate vicinity of the ship may occur.

Echo sounder array for mapping krill distributions

Based on a commercial system in wide use, consisting of single beam echo sounders with frequencies of 38, 70 120 and 200 kHz. The system has source levels of 230 dB re 1 μPa @ 1m, 4 ms pulse length, and around 7° beam width.

The matrix (Table V) is similar to the 12 kHz system above but with a smaller volume affected and greater absorption of the outputs. Again, the volume affected by the echo sounder indicate that TTS is possible only in a small volume up to a few metres immediately under the tranducers, making Level 4 and above impacts Inconceivable. Some minor displacement may occur in the area immediately adjacent to the vessel.

Multibeam echosounder

We considered mid range and full ocean depth multibeam systems with frequencies of 12 kHz, and 30 kHz, and source levels of ~236 dB re 1 μPa @ 1m (Table VI). These figures

Table VI. Consequences/Likelihood matrix for mid to full ocean depth multibeam echosounders.

	Consequences					
Likelihood	1.	2.	3.	4.	5.	6.
A	X					
B						
C		X				
D						
E			X	I?		
F				P	P/I?	X

Table VII. Consequences/Likelihood matrix for 3.5 kHz sub-bottom profiling echo sounder.

	Consequences					
Likelihood	1.	2.	3.	4.	5.	6.
A	X					
B						
C						
D		X				
E			X	I?	I?	
F				P	P	X

are based on two commercial systems in common use. The mid depth (< 3000 m) multibeam sonar operates at a frequency of 30 kHz and has a swath width of 150° x 1°. Echo sounder pulses (pings) are emitted every 4–8 seconds depending on water depth and are of short duration (0.7–15 milliseconds). The deep water system operates at 12 kHz. It has a swath width of 120 degrees. Echo sounder pulses (pings) are emitted every 4–8 seconds depending on water depth and are of short duration (2–20 milliseconds).

The high output and broad width of the swath abeam of the vessel makes displacement of animals more likely, although the for and aft beam width of multibeams are still small and the pulse length very short, so the risk of ensonification above TTS levels is still quite small, so the likelihood of auditory or other injuries seems low. Displacement might occur in the form of displacement from the survey area for days during the systematic mapping of an area. Level 4 impacts might conceivably occur to individuals in narrow sea ways where animals could be driven onto islands or held near the surface as has been suggested for beaked whale stranding events involving military systems. The probability of herding or holding animals near the surface is reduced by the restricted beam shape, which would make it unlikely that an animal would be exposed for more than a few minutes during passage of the vessel. The meeting could not see how populations could be affected adversely to Level 4 or 5 but was less confident that there would be no rare fatalities caused by herding, hence the I? for level 5. This should be compared to the likelihood of ship strikes to gain a perspective of the risks.

Sub bottom profiler 3.5 kHz

We considered a typical sub-bottom profiler with out put of 204 dB re 1 μPa @ 1m, 30° beam width and pulse lengths of 1, 2 and 4 ms. This type of sounder has been common on research vessels for decades. We thought that risks posed by a sub-bottom profiler were similar to other single beam systems though risks for individuals may be slightly higher because of the wider beam width and lower frequency content (Table VII). TTS data indicate that animals would require 250 to 1000 pulses to produce TTS.

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Table VIII. Consequences/Likelihood matrix for a small seismic reflection system using 2 small airguns.

	Consequences					
Likelihood	1.	2.	3.	4.	5.	6.
A	X					
B		X				
C			X			
D						
E				I	I?	
F				P	P	X

Small seismic system - 2 air guns

Some research activities in the Antarctic have employed small airguns to obtain high resolution seismic data. The system we considered was one for which characteristics were available. It comprises 2 GI (Generator Injector) guns. GI guns use a 45 cu. inch generating chamber. The output from 2 GI guns working together is a maximum of 229 dB re 1 µPa @1 m (measured zero to peak pressure, 0-p). Though there is some focusing of airgun sound downwards, the beam shape is not as well constrained as for transducer-based equipment so the group decided to treat airguns as effectively omnidirectional. The area > 180 dB re 1 µPa would be approximately 50 m in radius (LGL 2003). Ships towing seismic systems typically move at between 5 and 8 knots.

The small airgun system considered here would have a similar likelihood of severe impacts to multibeam surveys in that some herding and trapping of animals would be necessary (Table VIII). Lesser impacts would be more likely than multibeam because of frequency content and the near-omnidirectional nature of the beam however slow ship speed would facilitate avoidance.

Large airgun array

We considered a very large airgun array of 8575 cu inches with a source level of 256 dB re 1 µPa @ 1 m (0-p) (far field), lines spaced tens of kilometres apart, ship moving at 5 knots. The petroleum industry may use much closer line spacings, but broad line spacings are likely to be the norm in Antarctic waters for the foreseeable future. The area > 180 dB re 1 µPa would be approximately 900 m in radius (LGL, 2003). Typical arrays used by the petroleum industry in the order of 4000 cu. inches and have source levels of around 240 dB re 1 µPa @ 1 m (0-p) (far field). The array under consideration is based on one of the largest operating in a research context and has not been deployed in the Antarctic to our knowledge.

Table IX. Consequences/Likelihood matrix for a large seismic reflection system.

	Consequences					
Likelihood	1.	2.	3.	4.	5.	6.
A		X				
B			X			
C						
D						
E				I	I	
F				P	P	X

Table X. Consequences/likelihood matrix for a large chemical explosion.

	Consequences					
Likelihood	1.	2.	3.	4.	5.	6.
A				I		
B					I	
C						I
D						
E					P	P
F						

Large airgun surveys are certainly known to displace animals ranging from cetaceans to fish (Table IX). The duration of displacement will depend on survey design. Closely spaced lines in a small area as with 3-D surveys would mean that displacement from a region for the duration of the survey is highly likely, however 3-D surveys are unlikely in the Antarctic for the foreseeable future. A large airgun array produces sound levels probably in excess of those needed to damage animal hearing although the near-field sound is spread between the 20 airguns over several hundred square metres and source levels do not reach the level calculated for the far-field figure. Animals may still approach the array, (McCauley *et al.* 2000) so that mitigation measures should be used to reduce the impact on individual animals. The Action Group did not think severe impacts on populations likely.

Large chemical explosion

The workshop considered a large chemical explosion, not because such an activity is likely or acceptable, but to provide a "sensitivity test" for the method. We based this risk evaluation on a seismic refraction experiment with 10 tonnes of chemical explosives in 1976 in the North Pacific. Such refraction data are now collected using air guns or by seismic tomography using natural earthquakes. There are no records of biological effects or source level, however such a large charge would likely produce very high peak pressures and chemical explosions have a very rapid rise time compared to other sources.

The action group considered that serious impacts on individuals would be likely and that severe population impacts were also possible (Table X).

Submarine detection sounder

This risk matrix is based on published information on the ANSQS 53C, one of the ASW units associated with a

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Table XI. Consequences/Likelihood matrix for an antisubmarine warfare echo sounder similar to those implicated in mass stranding events.

	Consequences					
Likelihood	1.	2.	3.	4.	5.	6.
A						
B						
C				I	I	
D				P	P	I
E						P
F						

Table XII. Consequences/Likelihood matrix for shipping operations, including ice breaking.

	Consequences					
Likelihood	1.	2.	3.	4.	5.	6.
A	X					
B		X				
C			X			
D				I	I	
E						
F				P	P	X

number of stranding events (Balcombe & Claridge 2001, Evans & England 2001). Source levels are ~235 dB, frequencies are 2–4.5 kHz, and pulse lengths can be quite long compared to most scientific echo sounders, in the order of 1–2 s, depending on conditions and the beam width is about 30° with the transducer oriented approximately horizontally.

This sonar is one of the units implicated in some mass strandings of beaked and other whales. While the exact nature and causes of injuries inflicted on the whales involved one of these stranding incidents is the topic of debate (Jepson *et al.* 2003, Piantadosi & Thalmann 2004, Fernández *et al.* 2004), the association with AWS exercises is clear (Table XI). The differences between the characteristics of the AWS system and scientific echo sounders may provide some clue as to why the AWS system causes problems. The very long pulse lengths compared to scientific echo sounders would make the AWS system likely to produce TTS in marine mammals and for it to be perceived as "loud" and therefore cause displacement over a larger area than shorter pulse lengths. The orientation of the beam would make it more likely to ensonify animals in the area. Standard naval anti-submarine search patterns aim to ensonify large volumes of the upper part of the ocean (S. Dutton, personal communication 2004). This, taken with the higher speed of naval vessel operations compared to scientific surveys, would make it more likely to ensonify any animals in an area and make avoidance of high sound levels more difficult.

Shipping

We considered the risk of Antarctic shipping operations, including noise and the potential for ship strikes. Sound source levels can reach up to 200 dB re 1 µPa @ 1 m for ice breaking activities.

The level 4 to 5 risk for individuals reflect anecdotal evidence for ship strikes, mostly involving pack ice seals and penguins during ice breaking (Table XII). For cetaceans, ship collisions are regarded as a known risk globally (Clapham *et al.* 1999). This is likely to be lower for Antarctic resupply and research vessels because they are slower than many modern cargo vessels. Risks to populations were considered to be very low.

Discussion

The risk matrices for notional individual scientific surveys suggest a low level of risk for populations of animals in the Antarctic so that there was no justification for a blanket ban on acoustic technology used in marine research in the Antarctic. Most scientific instruments have a potential risk lower or comparable to shipping, so that to ban such activities while still visiting the Antarctic by ship would produce no real reduction in environmental footprint. Ceasing the use of acoustic technology would forgo the benefits of research of value in environmental protection and hydrographic mapping for safe navigation.

The risk assessment provides a clear case for scrutinising proposals that plan to use equipment with high source levels, low frequency, long pulse lengths and broad beam patterns. Mitigation strategies are necessary to minimise the risks posed to individual animals that approach such equipment and extra care should be taken in narrow seaways where animals may have difficulty avoiding the source. Equipment with characteristics similar to the AWS systems implicated in stranding events constitute a high risk and it is hard to conceive of an occasion when a large explosive charge would be acceptable.

Many documents addressing the impacts of anthropogenic sound in the marine environment emphasise the lack of knowledge of many effects and the potential long term, chronic impacts of high noise levels. The workshop reviewed the known levels of human activity in the Antarctic compared to other parts of the globe and concluded that Antarctic activities were so low that any impact was unlikely. For example, it is still difficult to define what impacts have occurred in the northern Gulf of Mexico where about several hundred thousand line kilometres of seismic data are recorded each year using large airgun arrays (e.g. Continental Shelf Associates 2004). This is more than the total collected in Antarctic waters since the first survey in 1979.

The results of the risk analysis and consideration of the associated uncertainties tend to support the recommendations on managing marine acoustic surveys originally put by the SCAR Acoustic working Group in 2002 (SCAR 2002). This report recommended mitigation strategies commonly used around the world be employed in

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the Antarctic, such as "soft" starts for equipment and shut down distances to protect individual animals that approach vessels. The best way to maintain the state of the Antarctic and avoid unforseen impacts is to utilise existing data sharing arrangements to avoid repeat surveying of areas with high source level equipment in consecutive seasons. The Antarctic Treaty and SCAR have mechanisms in place to ensure data are publicly available after a short period. For example, seismic data are available via the SCAR Seismic Data Library System (SDLS). An additional measure is a mechanism for dissemination of survey plans in order to avoid several surveys converging on the same area in the same season.

Conclusions

1. This risk analysis indicates that the risks of most *scientific* acoustic techniques likely to be used in the Antarctic were less than or comparable to shipping activities on their own.
2. Even airgun seismic surveys were not considered a threat to populations.
3. Survey planning and mitigation measures could be used to reduce the risk to individual animals posed by the higher risk equipment.
4. Any long term cumulative effects can be mitigated by minimizing repeat surveying through existing data sharing arrangements and survey planing measures.

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