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The Use Of Sound Propagation Models To Determine Safe Distances From A Seismic Sound Energy Source

Utilisation de modèles de propagation du son pour déterminer les distances sécuritaires de la source d'émission des sons sismiques

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ABSTRACT

To assess how seismic sounds used in petroleum exploration may affect wildlife, it is necessary to estimate received sound levels for the variety of ranges and depths where animals might be located. The apparent loudness of a noise source is determined by the radiated acoustic power, the propagation efficiency, the ambient noise, and the hearing sensitivity of the subject species. The amplitude of seismic sounds usually declines with distance from source, and is largely dependent on the frequency characteristics of the signal. Several factors determine the amount of weakening of seismic array sounds with distance including geometrical spreading, transmission/reflection, absorption, and scattering. Information on geology, seabed characteristics, sediment properties, and bathymetry are critical in determining acoustic propagation losses and received sound pressure levels. Sound propagation and ambient noise conditions are highly variable within and among areas, and a pan-regional “one-criteria-fits-all” regulatory approach is likely not a risk-averse management approach. Studies described in this document will support a conclusion that, while model predictions can be useful for planning and for preparing environmental impact statements, given the discrepancies between modelled and measured sound propagation it is advisable to obtain relevant empirical data as well. The document describes approaches that could improve the effectiveness of seismic sound modelling.

RÉSUMÉ

Afin d’évaluer l’incidence des sons sismiques produits lors de l’exploration pétrolière sur la faune, il est nécessaire d’estimer les niveaux sonores captés pour la multitude d’aires de répartition et de profondeurs que peuvent fréquenter les animaux. La sonie apparente d’une source de bruit est déterminée par la puissance acoustique émise, l’efficacité de la propagation, le bruit d’environnement et la sensibilité auriculaire de l’espèce étudiée. En règle générale, l’amplitude des sons sismiques diminue avec la distance de la source et elle dépend fortement des caractéristiques liées à la fréquence du signal. Plusieurs facteurs permettent de déterminer le degré de diminution de l’intensité de la source sismique avec la distance, notamment la propagation géométrique, la transmission/réflexion, l’absorption et la diffusion. Les renseignements sur la géologie, les particularités des fonds marins, les propriétés des sédiments et la bathymétrie constituent des éléments essentiels dans la détermination des pertes de propagation acoustique et des niveaux de pression des sons captés. La propagation du son et les conditions de bruit d’environnement varient énormément d’une zone à une autre et au sein d’une même zone; par conséquent, une approche de réglementation panrégionale « universelle » ne constituerait probablement pas une approche de gestion prudente. Les études décrites dans ce document appuient une conclusion voulant que, bien que les prédictions d’un modèle puissent être utiles pour planifier et préparer des énoncés visant les impacts environnementaux, étant donné les écarts entre la propagation sonore modélisée et mesurée, il est conseillé d’obtenir également des données empiriques pertinentes. Le document décrit des approches qui pourraient améliorer l’efficacité de la modélisation des sons sismiques.

BACKGROUND

To assess how seismic sounds used in petroleum exploration may affect wildlife, it is necessary to estimate received sound levels for the variety of ranges and depths where animals might be located. The audibility or apparent loudness of a noise source is determined by the radiated acoustic power (source level), the propagation efficiency, the ambient noise, and the hearing sensitivity of the subject species (e.g., Au and Hastings 2009; Etter 1996; Ward 2000). This working paper focuses on propagation.

Noise levels produced by human activities in underwater and terrestrial environments are determined not only by their acoustic power output but, equally important, by the sound transmission conditions (e.g., Malme 1995). A moderate-level source transmitting over an efficient path may produce the same received level at a given range as a higher-level source transmitting through an area where sound is attenuated rapidly. Likewise, a given noise source operating in different areas, or in the same area at different times, may be detectable for greatly varying distances, depending on regional and temporal changes in sound propagation conditions among other factors. As a result, the zone of acoustic influence for a given source of man-made noise can vary in radius 10-fold or more, depending on operating site and depth, and on seasonal changes in water properties (Malme 1995; Ward 2000). Hence, sound transmission measurements, analyses, and model predictions are necessary to estimate the potential radius of acoustic influence of noisy human activities.

Model predictions can be useful for planning and for preparing environmental impact statements, but given the discrepancies between modelled and measured sound propagation (see examples below) it is advisable to obtain relevant empirical data as well. This is important because of the highly variable and site-specific nature of underwater sound transmission, especially in shallow water. In the relatively shallow waters of the continental shelves the acoustic properties of the seabed become the dominant factor, but there are only a few locations where the relevant substrate properties have been adequately determined.

On continental shelves, primarily 10-Hz sound energy is received over distances exceeding 45 km; it is likely that the 10-Hz energy travels almost exclusively along a path in the bottom sediments (Greene et al. 2000). A complication within the Arctic continental shelf areas is that it is probable that “relic permafrost” occurs sporadically in the subbottom (Neave and Sellman 1984), and this can result in anomalously low sound transmission loss patterns in these areas.

Sound refraction is the dominant feature of deep water sound transmission. Variation of sound speed with depth controls the sound ray paths. As a result, the decrease of sound intensity with range is influenced not only by spreading loss but also by concentration or reduction in the ray density due to refraction. In contrast, seismic sound transmission in shallower water, such as those found on Canada’s continental shelves, is highly variable and site-specific because it is strongly influenced by the acoustic properties of the bottom (e.g., Duncan and McCauley 2000) and surface conditions as well as to a lesser extent by variations in sound speed within the water column. In deep water, increasing pressure and variations in temperature and salinity with depth cause sound rays to be refracted downward and upward, creating a sound speed minimum and thus propagation channel. However, shallow depth does not allow most types of sound channelling effects noted for deep water. Refraction of sound from the bottom and surface interfaces in shallow water results in either reduced or enhanced sound transmission (e.g., Vadov 2002). With upward refraction, bottom reflections and the resulting bottom losses are reduced; with downward refraction the opposite occurs. Thus, sound transmission conditions in continental shelf areas can vary widely (see a comparison of Scotian Shelf and Grand Banks propagation data in Lawson and McQuinn 2004; Ellis and Chapman 1980).

In summary, the amplitude of seismic sounds usually declines with distance from the airgun array. This diminishment of the signal with distance is largely dependent on the frequency characteristics of the signal, with stronger attenuation of the higher frequencies of the broadband seismic sounds. Several factors determine the amount of weakening of the seismic array sounds with distance including *geometrical spreading* (sound energy decays at a rate proportional with the inverse of distance squared), *transmission/reflection* (pressure waves will be transmitted into the sea bottom, and be reflected from the geological boundaries, with variable changes in signal properties), *absorption* (transmission loss due to frictional dissipation and heat is an exponential function of distance), and *scattering* (reflection, refraction, and diffraction from variations in the propagating medium cause a transmission loss). Information on geology, seabed characteristics, sediment properties, and bathymetry are critical in determining acoustic propagation losses and received sound pressure levels. This highlights the concept that sound propagation and ambient noise conditions are highly variable within and among areas, and illustrates that a pan-regional "one-criteria-fits-all" regulatory approach is likely not a risk-averse management approach. (A particular seismic operation might be acceptable in one area, but not in another based on the sound propagation or biological characteristics of the area.)

REAL-WORLD PERFORMANCE OF SOUND PROPAGATION MODELLING

Sound propagation research has made considerable progress in recent years, with field measurements of sound levels in relation to distance, frequency, and environmental parameters having been obtained in many areas and situations (e.g., McQuinn and Carrier 2005; Tyack et al. 2006; Deveau et al. 2008). Efficient computer models have been developed based on these data and on theoretical considerations (e.g., Etter 2001). Some models have provided sufficient detail to account for many of the propagation processes occurring in the field. However, most models are designed for specialized applications (often classified) and are not easily generalized for use in predicting potential noise impact ranges for anthropogenic sources. Further, acoustical expertise is needed to apply most specialized propagation models. If propagation losses and received levels at long range must be predicted, especially in shallow water, site-specific empirical data on bottom and water properties are still needed.

To understand the efficacy of this modelling process it is instructive to review a sample of recent studies of modelled and measured underwater sound propagation.

A NON-SEISMIC EXAMPLE OF PROPAGATION VARIABILITY

A recent study of the propagation of sounds from several types of acoustic deterrent devices (used to deter marine mammals from human fishing activities) demonstrated some surprisingly large variation (up to 30 dB, or a five fold variation) in sound levels as they propagated in a nearshore environment. Shapiro et al. (2009) conducted a series of recordings at increasing distances from several types of underwater pingers in the UK. It was not surprising that they found that received sound levels did not increase simply as the distance to the source changed, but varied. The range of these fluctuations was up to 30 dB, with many fluctuations in the 10 to 15 dB range (Fig. 1). The sound exposure levels varied within very short distances, likely as a result of the interference of surface reflection and rays reflected from the seabed (Wahlberg 2006). Since managers tasked with protecting marine mammals from defined anthropogenic sound exposures are concerned about physiological and behavioural effects resulting from such exposure, it is extremely important to acknowledge that real-world exposures can vary to the extent recorded in this experiment. Shapiro et al. (2009) stated:

"The overall trend of decreasing SEL with increasing range from the (source) ... was disrupted by interference patterns. Such variability and deviation from spherical or cylindrical spreading expectations, even at large distances from the source, conflicts with the classic description of concentric zones of increasing disturbance with decreasing range (Richardson et al. 1995). This also poses a difficulty for an animal attempting to predict level on a fine scale and orient with respect to this variable intensity gradient. The spatial extent of these zones is clearly difficult to predict, especially given the plasticity of an animal's thresholds of detection, injury, and avoidance resulting from its motivation, behavior, and physiological state." (pp. 61-62)

Seismic Sound Modelling

For sound sources with significantly louder source levels, I next examine results from a number of modelling and measurement studies of seismic sound propagation.

Western Beaufort Sea, 1996-2000

During the period of 1996-2000, extensive 3-D seismic exploration was carried out in the western Beaufort Sea. As required by National Marine Fisheries Service (NMFS), the seismic operators were required to conduct both modelling and follow-up field measurements of sounds that propagated at various distances from these airgun arrays.

Field measurements made in the western Beaufort Sea varied from year to year (Table 1) and differed from model predicted values (Table 2) The larger airgun array towed by *Arctic Star* radiated weaker sounds than expected whereas, the 190 and 180 dB radii around *Saber Tooth* were double to triple those predicted and to those estimated for *Arctic Star*. This occurred even though *Arctic Star* towed twice as many airguns (16 vs. 8 for *Saber Tooth*) and almost three times the airgun volume (1500 in^3 vs. 560 in^3 for *Saber Tooth*). The surprisingly high source strength of the *Saber Tooth* array in the horizontal plane may have resulted from its configuration. The eight guns towed by *Saber Tooth* were compactly spaced compared to *Arctic Star's* 16 guns. In addition to this array effect, the vertical alignment of the individual airguns may also have increased horizontal radiation compared with the horizontally aligned *Arctic Star* airguns.

Overall, the modelled propagation strengths rarely approximated the actual received sound levels. The safety radii for the 180 dB exposure level (defined by NMFS as the received level above which cetaceans might be expected to exhibit temporary changes in hearing sensitivity) were contained within the 500 m distance proposed in the Canadian Statement of Practice half of the time. When these arrays were operated in shallow water the safety radii could be twice as large as 500 m (Table 2). As for the acoustic deterrent studies discussed previously, the seismic sound pulses detected at long ranges had highly variable received levels.

Canadian Beaufort Sea, 2001-10

Similar disparities between modelled and measured sound propagation from seismic sources have been reported during recent exploration in the Canadian Beaufort Sea (e.g., McGillivray et al. 2007). A summary of the modelled and measured propagation of seismic sounds illustrates the frequent disparity between these two values in the Canadian Beaufort Sea (Table 3). In almost all cases, the 180 dB safety zone was set at a distance greater than the 500 m recommended in the Canadian Statement of Practice – particularly for deeper water. Of most concern, in shallow nearshore waters the 180 dB safety zone is as great as two km (Fig. 2). These disparities notwithstanding, the geographic variation in seismic sound propagation is significant.

A comparison of modelled and measured sound propagation from a 4,128 in^3 airgun array demonstrates the differences at the 160 and 170 dB radii (Table 4), with mean measured distances being 25-56% greater than that which was modelled. The same pattern was evident for the 180 dB radii, with and without the inclusion of a correction for the presence of subbottom permafrost (Table 5). Only when the measures were conducted at greater distances from the seismic source did the modelled range to the 180 dB radius exceed the measured range. As for the historic data, in this study of the 1,428 in^3 airgun at this site, the measured distance to the 180 dB received level threshold was much greater than 500 m.

The Imperial (Ajurak) Beaufort 3D seismic programme was conducted in 2008 in a location approximately 120 km north of the outermost edge of the Mackenzie River delta in the Beaufort Sea. It included a portion of the sloping edge of the Beaufort Shelf, and water depths ranged from 60 to 1200 m. (Table 6). It can be seen in Table 6 that the Project Description/EA predictions for the 180 dB radii were consistently larger than what was measured in the field during sound source verification (B. Wheeler, Stantec, Burnaby, B.C. pers. comm.). Unfortunately a sound source verification for shallow water was not obtained.

Such disparities have led some industrial proponents to derive their own appropriate safety zones based on modelling and field measurements, rather than employ the 500 m safety zone in the Statement of Canadian Practice:

> *12.2.6 Selection and Implementation of Safety Zones*
> *12.2.6.1*
> *To minimize the potential for hearing or other damage in whales, seismic operations will be shut down (or delayed) temporarily if bowhead or beluga whales are sighted within a pre-determined "safety" zone around the seismic array. Recently, a "Statement of Canadian Practice with respect to the Mitigation of Seismic Sound in the Marine Environment" (hereafter referred to as the Statement) was issued by the Canadian Federal Government. The Statement (section 6a) says that a proponent must "establish a safety zone which is a circle with a radius of at least 500 metres as measured from the centre of the air sources array(s)". However, no information is provided as to how this 500 m distance was derived. As in 2006-2008, GXT is undertaking an acoustic modeling study to asses sound levels from the proposed airgun array to derive appropriate safety zones.*

Gulf of Mexico, 2002-03

In a series of field experiments conducted in 2002 and 2003, tagged sperm whales (*Physeter macrocephalus*) were exposed to airgun pulses in the Gulf of Mexico, while they carried attached tags providing acoustic recordings at measured ranges and depths (DeRuiter et al. 2006). Ray trace and parabolic equation models provided information on the paths of propagated sounds. With adequate environmental information, a broadband acoustic model predicted the relative levels of multipath arrivals recorded on the sperm whales. Airguns sometimes exposed these whales to sound energy at frequencies above 250 Hz, and source and environmental parameters influenced the characteristics of received airgun pulses. More pertinent to this review, on-axis source levels and simple geometric acoustic spreading did not adequately explain airgun pulse propagation and the shape and magnitude of exposure zones – measured and modelled received sound levels differed, at times by several fold.

Sable Gully, 2003

Plans for conducting 3-D seismic exploration adjacent to the Sable Island Gully Marine Protected Area (MPA) on the Scotian Shelf of eastern Canada prompted concerns over the potential for stress or physiological harm to the endangered northern bottlenose whale (*Hyperoodon ampullatus*) from exposure to these sound sources. A study of the far-field measurement of seismic pulses throughout the Gully MPA and specifically the Gully Whale Sanctuary was therefore initiated to directly measure noise levels produced by the seismic pulses and to validate the accuracy of sound propagation predictions published in the environmental assessment (McQuinn and Carrier, 2005). Results showed that the noise levels predicted using acoustic models were on average underestimated by 8 dB (Table 7). This finding is significant since the results of sound propagation models are used by regulators to define a safety radius for marine mammals around seismic arrays. The highest average sound pressure level (RMS) measured in the Gully MPA during the McQuinn and Carrier (2005) study was 145 dB re 1µ Pa at 90 m depth, 50 km from the seismic array within the Gully Whale Sanctuary (Fig. 3). It was estimated that sound levels in the Whale Sanctuary would have been between approximately 153 and 157 dB when the vessel was at its closest approach to the Gully. The "worst case" sound level at the Gully MPA boundary, i.e., 0.8 km from the source, extrapolated from near-field measurements would have been approximately 178 dB, or 14 dB higher than originally predicted in the project Environmental Assessment (EA) and close to the 180 dB safety criteria. Measured sound levels were also significantly higher than the model predictions at several other stations and showed significant variability around the mean values. This demonstrates the importance of using accurate model input data and field validation to verify the model predictions as well as the need to measure the variability around the mean sound level estimates.

This Gully study reflects previous concerns that seismic surveys conducted in and around canyons will result in sound reflections from the canyon walls that will produce convergence and shadow zones in a complex and dynamic manner, given a mobile sound source. Sound propagated towards shallow shelf areas at the boundaries of the canyons will be attenuated, creating shadow areas beyond them where the noise is significantly reduced (Fig. 3). Conversely, sound that is channelled into canyons will be reflected off the hard, vertical walls, facilitating the ducting of the sound vertically, just as thermal sound channels duct the sound horizontally. Since the sound source is mobile, sound will reflect off the canyon walls at varying angles, rendering modelling of propagation patterns to be quite dynamic. This Gully study supports suggestions that differences between model-predicted and measured sound levels can be of the order of 10-15 dB in such marine canyons.

DISCUSSION

Seismic exploration sounds have the potential to produce immediate behavioural and/or physiological effects on marine mammals. Estimating the distance from a seismic array at which such effects might occur is a task common to all three categories of mitigation measures integral to the Canadian Statement of Practice (Planning Measures, Operational Measures, and Application of additional site-specific measures required by the site-specific environmental assessment of a seismic project). For managers and proponents alike, modelling propagation is a cost-effective mitigation measure only if it is accurate enough to facilitate sound exposure predictions that would result in little risk to listed marine mammal species in the operating area.

When comparisons are made between modelling and measurement, it is important to ensure that they are comparable (e.g., measurements are taken in the same area that is applied in the model).

Context is an important element of the comparison. There is a need to standardize the method that is currently being used to measure sound in the water. This will help address the difficulties that exist in comparing data. In addition, participants at this meeting emphasized the need for highly skilled and experienced people to gather these data.

CONCERNS RAISED BY SEISMIC SOUND MODELLING

Despite the appeal of often-complex acoustic modelling approaches, it is clear that information gaps exist in descriptions of acoustic characteristics of marine areas of interest and the efficacy of underwater sound propagation models. These gaps have resulted in a high degree of uncertainty in the modelling of anthropogenic impacts. In many cases, modelled and actual propagation values do not approximate each other very well. As such, a precautionary approach to regulation is required.

Information on geology, seabed characteristics, sediment properties, and bathymetry are critical in determining acoustic propagation losses and received sound pressure levels. This highlights the concept that sound propagation and ambient noise conditions are highly variable within and among areas, and illustrates that a pan-regional "one-criteria-fits-all" regulatory approach is likely ill-advised, as a particular seismic operation might be acceptable in one area, but not in another based on the sound propagation or biological characteristics of the area.

The difficulty in predicting underwater acoustic propagation is evident in the review of seismic sound studies presented in this document. For instance, in the relatively shallow waters of the continental shelves, the acoustic properties of the seabed become the dominant factor (Duncan and McCauley 2000), but there are only a few locations where the relevant substrate properties have been determined adequately.

It is important to realize that due to the complex patterns of sound propagation in these diverse regions, some marine mammals may not necessarily encounter the average sound exposure conditions predicted for a seismic survey. Therefore we must determine and be sensitive to the worst-case conditions that can be encountered to ensure that we do not underestimate the impact upon a particular segment of a marine mammal population. Especially when we are dealing with SARA-listed species, detrimental effects suffered by one individual can easily translate into detrimental effects on the population; in critical situations (e.g., the northern right whale and blue whale), the reduced fitness or loss of a single individual becomes a concern for the health and productivity of the population. The precautionary approach (e.g., safety radius at 500 m) was designed for these circumstances. DFO is responsible to provide the necessary precautionary regulations and mitigation measures to ensure that no additional pressure is exerted on populations already at risk. This may entail extraordinary measures when endangered species are involved in critical behaviours (e.g., calving, feeding and migration), which might include closed areas and seasons, or operational shut downs when detection probabilities fall below certain standards due to sub-optimal observation conditions.

The three categories of mitigation measures integral to the Canadian Statement of Practice can fail to provide a precautionary level of protection to marine mammals if the problems inherent in modelling seismic sound propagation are not considered when setting so-called safety radii. Fixed radii values may not be accurate, broadly applicable, or precautionary given the variability of sound propagation revealed in these studies.

IMPROVING THE EFFECTIVENESS OF SEISMIC SOUND MODELLING1

There are a number of ways in which the efficacy of sound modelling (for both the source and propagation of sound from the source) could be improved:

- o modelling of both the magnitude and frequency characteristics of seismic source output at relevant points in space and time (e.g., to minimize output from seismic source to get the job done) and seismic signal propagation must be an integral component of the pre-survey seismic operations planning process to achieve maximum utility (based on risk assessment prepared as part of the project environmental assessment, such modelling may not be required for every survey, but if it is, it should be done in this manner)

- o sufficient background information must be available to support effective modelling and includes: (1) geophysical and oceanographic data, (2) distribution of noise source and biological receivers in space and time, and (3) range of variation in this information

- o the choice of propagation model should be applicable to the intended operating environment and frequency range

- o cumulative Sound Exposure Level (SEL) is a more biologically relevant metric for sound modelling and describing model output (than just root mean square [rms] alone, although rms values can be used to compare model output with older datasets/criteria if details were specified); models should be capable of producing at least both of these metrics. Note: Even these output parameters need to be standardized. Additional needs should be reviewed before modelling starts)(SEL, peak sound pressure level, M-weighting, and rms are all metrics that should be considered). Further, modellers should look at cumulative sound energy exposures over time; this may be challenging but is an important consideration

- o sound models can be more applicable if they are linked to a set of practical mitigative criteria (e.g., shutdown radii) that can be operationalized (e.g., can we detect whales by species or at distances necessary to use the modelled criteria? Can we define broad receiver hearing categories to facilitate field monitoring by MMOs?). There is a need for practical criteria that can be implemented effectively in the field. Modelling is a useful tool for determining what will be practical and effective

- o in modelling impacts, to the fullest extent possible, use information on the species and conditions that are present in an area; when information specific to the particular application is not available, many experts consider Southall *et al*. a good starting point

- o to date, modelling has focused on hearing impacts. A desirable approach should include exposure criteria that employ receiver hearing weighting (e.g., M-weighting) for sensitive or important marine species – factor in the identities and hearing capabilities of key receivers in the modelling exercise

- o modelling will be significantly less effective where source-specific, operations area-specific, or species-specific data are not available to parameterize the model

[1] these summary points where derived using a breakout group, followed by review by all workshop attendees, and revision to produce a workshop consensus

- although seismic airgun arrays are known to have high frequency components, most current seismic source models demonstrate their best predictive scope in the lower end of the acoustic frequency range (≤200 Hz); further work should be invested in high frequency source modelling (underway now) to better match model operational range to the broadband output of seismic arrays and the hearing ranges of species of interest

- although seismic airgun arrays are known to have high frequency components, most current seismic source models demonstrate their best predictive scope in the lower end of the acoustic frequency range (≤200 Hz); further work should be invested in higher frequency (e.g., >10 kHz) source modelling (underway now) to better match model operational range to the broadband output of seismic arrays and the hearing ranges of species of interest. Impacts of concerns are not restricted to the range where current models work well; this is a limitation of current modelling at this point

- several factors would necessitate field verification of the model(s):
  - SARA-listed species (receptors) present in the area expected to be ensonified
  - seismic operations expected to occur in shallow water (defined as <200m)
  - no previous field verification of the model or context
  - seismic operations expected to occur in non-uniform areas (with respect to geophysical and/or seasonal characteristics)
  - multiple operations might necessitate studies of long-range propagation (although the CSOP stipulates a 500m baseline)

- at present, field verification methods are not standardized and often inconsistent. Thus, standardization of methods is necessary, recognizing that results will be expected to have high variance (e.g., natural context, sound variances). Field verifications would be more useful if standards were developed and utilized so that verifications could be compared

- data currently being collected might provide useful real-time information that could be used to improve models. This should be investigated on a case-by-case basis. Examples of potentially useful data include: Ocean Bottom Seismic receivers (OBS – a set of receivers deployed on the ocean bottom to detect the signals from the airgun array) might provide useful field data on sound speed or seismic signal for verification of acoustic propagation models; towed seismic streamer data, or other near real time site-specific measures (e.g., XBTs, CTD casts) might provide useful real-time information about the acoustic properties of the water column for verification of the model

- To date, modelling has focused largely on hearing impacts. As knowledge accumulates over time, modelling should take other knowledge into account (non-auditory or behavioural impacts; or improved knowledge of auditory ranges etc.)

ANOTHER CONCERN: THE POTENTIAL EFFECT OF CLIMATE CHANGE ON SAFETY RADII

At the broadest possible scale, there is evidence to suggest that increasing ocean acidification will allow underwater sound to propagate further. Low- and mid-frequency sound absorption in the world's oceans has already decreased by 10-15% as ocean pH has been reduced by several things including increased CO_2 levels. This means that sound travels 10-15% further, with the effect that background ambient noise levels (predominantly wave and shipping noise at the frequencies being impacted) rise as the cumulative noise in any one location contains source noise from a larger area. The greatest impact is in sound below 1 kHz, with significant effects up to 10 kHz. Projections for the continued acidification and therefore further increases in sound propagation suggest that by 2050 (Figure 4; Hester et al. 2008), there will be a 30% increase in sound propagation distances (based on a low-end prediction of a decrease in pH of 0.15); more likely it is a 40-60% increase in sound propagation distances (Hester et al. 2008). This means that seismic sound propagation models will have to be modified, and safety radii for seismic operations may have to be reduced to accommodate these changing ocean characteristics.

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Table 1. Conservative field radii, for seismic array sounds in the western Beaufort Sea, 1996–1999. These are distances from airgun array sources, estimated using the strongest levels measured in field tests, beyond which received levels were expected rarely to exceed 190, 180 and 160 dB re 1 μPa SPL. Modified from Greene et al. (2000).

Array	Array Size (in^3)	Gun Count	Gun depth (m)	Water depth (m)	190 dB Radius (m)	180 dB Radius (m)	160 dB Radius (m)
Small arrays							
(1996)	720	6	3.5	10	94	450	1980
(1997)	720	6	3	6	158	445	1430
Saber Tooth (1998)	560	8	2	10	(S) 524	(B) 1524	(B) 5300
Large arrays at shallow tow depth							
(1996)	1320	13	3.5	10	257	1020	4900
Arctic Star (1998)	1500	16	2.3	8	(S) 93	(S) 396	(B) 2970
Arctic Star (1999)	1210	12	2.3	8	(B) 90	(B) 203	(B) 1716
Arctic Star (1999)	1210	12	2.3	23	133	511	3804
Arctic Star (2000)	1210	12	2.3	8	100	147	1770
Arctic Star (2000)	1210	12	2.3	23	159	538	3590
Large arrays at deeper tow depth							
Arctic Star (1998)	1500	16	5	8	(S) 267	(S) 729	(B) 4610
Arctic Star (1999)	1210	12	5	8	(B) 100	(B) 367	(B) 2310
Arctic Star (1999)	1210	12	5	23	(B) 246	(B) 921	(B) 5476
Arctic Star (2000)	1210	12	5	8	100	311	2530
Arctic Star (2000)	1210	12	5	23	261	863	4860

(S) denotes value from stern aspect; (B) denotes value from bow aspect.

Table 2. Marine mammal seismic exposure safety radii (re 1 μPa SPL) for seismic airgun arrays in the western Beaufort Sea. Shaded lines denote conservative (high) radii estimates based on field measurements. Modified from Table 3.3 of Greene et al. (2000).

Tow Vessel	Array Size (in^3)	Water Depth (m)	Airgun Depth (m)	190 dB Radius (m)	180 dB Radius (m)	160 dB Radius (m)	Source of Estimates
Predicted	750		2	170	660		IHA (NMFS 1998a,b)
Saber Tooth	560	10	2	(B) 188	(B) 1038	†(B) 5300	Measurements, nominal
Saber Tooth	560	10	2	(S) 524	(B) 1524	††(B) 5300	Measurements, high level
Predicted	1500		2	200	750		IHA (NMFS 1998a,b)
Arctic Star	1500	8	2	†(S) 63	(S) 300	(B) 2800	Measurements, nominal
Arctic Star	1500	8	2	†(S) 93	(S) 396	(B) 2970	Measurements, high level
Predicted	1500		5	350	1000		IHA (NMFS 1998a,b)
Arctic Star	1500	8	5	(S) 195	(S) 584	†(B) 4610	Prediction, nominal
Arctic Star	1500	8	5	(S) 267	(S) 729	††(B) 4610	Prediction, high level

(S) denotes value from stern aspect; (B) denotes value from bow aspect.
† Ranges fall outside the measured region and are estimated by extrapolation.
†† Nominal safety radius was greater than higher-level prediction; used nominal instead.

Table 3. Eastern Beaufort Sea cetacean safety radii values for operations in 2001-2010. Note the differing sound reference metrics used to describe the source level of the seismic arrays. Prepared by A. Joynt and L. Harwood, DFO.

Year	Array Size	Source Level (dB)	Water Depth (m)	*Modelled* Distance to 180 dB (m)	*Measured* Distance to 180 dB (m)	180 dB Safety Radius Used (m)	Reference
2001	2250 in^3	210	8.2 -16.5	1000	665 -1370	1000	Marine Mammal and Acoustical Monitoring of Anderson Exploration Ltd.'s Open Water Seismic Program in the Southeastern Beaufort Sea, 2001. LGL & JASCO, May 2002
2006	4128 in^3	239 (re1uPa @ 1m) 258 (0 to peak) 265 (peak to peak)	<500	1150	600-2200 [1]	1150	Environmental Assessment of GX Technology's Beaufort Span 2-D Marine Seismic Program Open-water Season 2006-2007. LGL TA4319-2. June 2006
			>500	1000		1000	
2007	4128 in^3	239 (re1uPa @ 1m) 258 (0 to peak) 265 (peak to peak)	map: pale green	500	see Tables 4 and 5 for error	500	Project Description for the Proposed GX Technology Beaufort Span 2-D Marine Seismic Program Open-water Season 2007. LGL TA4460-1. Mar 2007
			light green	500-1000		500-1000	
			bright green	1000-1500		1000-1500	
			blue	1500-2000		1500-2000	Preliminary Report on Sound Source Verification Measurements from GX Technology's 2007 Beaufort Sea Seismic Survey. JASCO. Aug 27, 2007
			pink	2000-2500		2000-2500	
2008	4128 in^3	239 (re1uPa @ 1m) 258 (0 to peak) 265 (peak to peak)	map: pale green	500	no modelling in 2008; safety radii same as 2007	500	Project Description for GXT 2D Seismic Program Beaufort Span Canada 2008 - Project Description for the NEB . Dec 2007
			light green	500-1000		500-1000	
			bright green	1000-1500		1000-1500	
			blue	1500-2000		1500-2000	
			pink	2000-2500		2000-2500	
2008	3192 in^3		65	1620		40-200	Beaufort Sea 3D Seismic Program Summer 2008 Project Description. Feb 2008
		200-250 (0 to peak)	350	850		200-500	
			750	500		500-1200	
2009	4450 in^3	238 (re1uPa @ 1m)	<100	1860			BP Exploration Pokak 3D Seismic Program - Project Description. Feb 2009
			100-400	1990			
			>400	1050			
2010	1500 in^3	230 (re1uPa @ 1m) 246 (0 to peak) 252 (peak to peak)	5	390			Project Description for the Proposed GX Technology Beaufort Ocean Bottom Cable 2-D Marine Seismic Program. LGL SA1008. Sept 2008
			15	520			
			others[2]	TBA			
		226 ($re1uPa^2$@1m)(SEL)					

[1] see p. 39 of the Deveau et al. (2008) for the changes to the safety radii. [2] modelling not yet complete for all depths, minimum safety radius of 500 m will be applied.

Table 4. Differences between measured and modelled eastern Beaufort Sea cetacean safety radii values (SPL_{90}) for a 4,128 in^3 seismic airgun system. GX Technology Corporation (2007).

Site A					
SPL_{90} (dB re µPa)	Estimated range west of CPA (km)	Estimated range east of CPA (km)	Mean range (km)	Modelled range (km)	Difference (km)
170 dB [(1)]	1.52	2.90	2.21	1.77	0.44 (+25%)
160 dB [(2)]	5.87	11.9	8.89	5.70	3.19 (+56%)

(1) *The distance to the 180 dB rms threshold could not be estimated from the data at site A1 because all SPL_{90} values measured at this station were less than 174 dB. Thus a comparison is presented for 170 dB rms instead.*
(2) *The model radii presented for comparison in the table are for a mid-water column receiver at 125 meters depth. Actual safety radii value should be taken from the modelling report because these were chosen to be the*

Table 5. Differences between measured and modelled eastern Beaufort Sea cetacean safety radii values (SPL_{90}; Test Site B) for a 4,128 in^3 seismic airgun system, accounting for subbottom permafrost structures in a clay bottom. GX Technology Corporation (2007).

Site B					
SPL_{90} (dB re µPa)	Estimated range west of CPA (km)	Estimated range east of CPA (km)	Mean range (km)	Modelled range (km) No PF / PF[(1)]	Difference No PF / PF[(1)]
180 dB	1.97	2.23	2.10	1.93 / 1.59	0.17 (+9%) / 0.51 (+32%)
160 dB	7.22	8.29	7.76	8.70 / 9.60	-0.94 (-11%) / -1.84 (-19%)

(1) *PF = Permafrost, No PF = No permafrost.*

Table 6. Comparison of model predictions, and field measurements, for the 180 dB_{rms} sound propagation distance from a seismic source during the 2008 Imperial (Ajurak) Beaufort 3D seismic programme (data provided by B. Wheeler, Stantec).

	Shallow Water (65 m)	**Intermediate Water** (350 m)	**Deep Water** (750 m)
Project Description Prediction	1,620 m	850 m	500 m
Field Verification Measurements	Not available	320 m (endfire*)	415 m (broadside*)

Table 7. Comparison of sound propagation model predictions, and field measurements in July, at various distances from a moving seismic source during the 2003 Sable Gully Study (from McQuinn and Carrier 2005).

Track Prediction	Range (km)	Predicted SEL+10 (dB)	Recording Station	Range (km)	Measured SEL+10 (dB)	Diff. (dB)
Track C (Jun)	50.0	145.3	E1	49.5	148.3	3.0
Track C (Jun)	50.0	145.3	E2	50.2	147.6	2.3
Track C (Jun)	60.0	136.6	E3	58.3	146.9	10.3
Track C (Jun)	70.0	135.0	E4	78.9	145.6	10.6
Track A (Aug)	30.0	138.7	F1	30.5	153.7	15.0
Track B (Aug)	30.0	134.5	F1	30.5	153.7	19.2
Track C (Jun)	30.0	143.4	F1	30.5	153.7	10.3
Track C (Jun)	60.0	136.6	F3	60.3	148.9	12.3
Track C (Jun)	70.0	135.0	F4	71.9	144.6	9.6

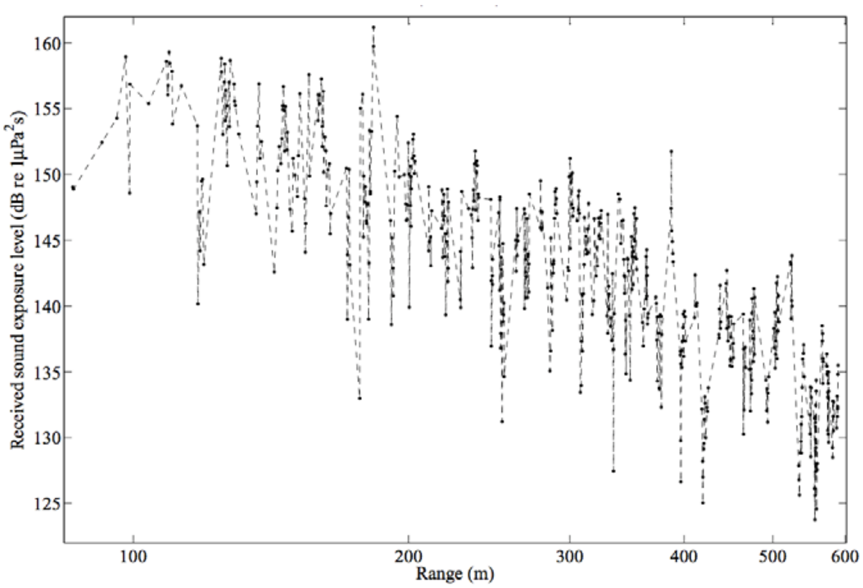

Figure 1. Received sound levels decline with distance from a Lofitech AHD source, although this decline is not consistent, and exhibits at least a 10-15 dB variation. Figure 5 in Shapiro et al. (2009).

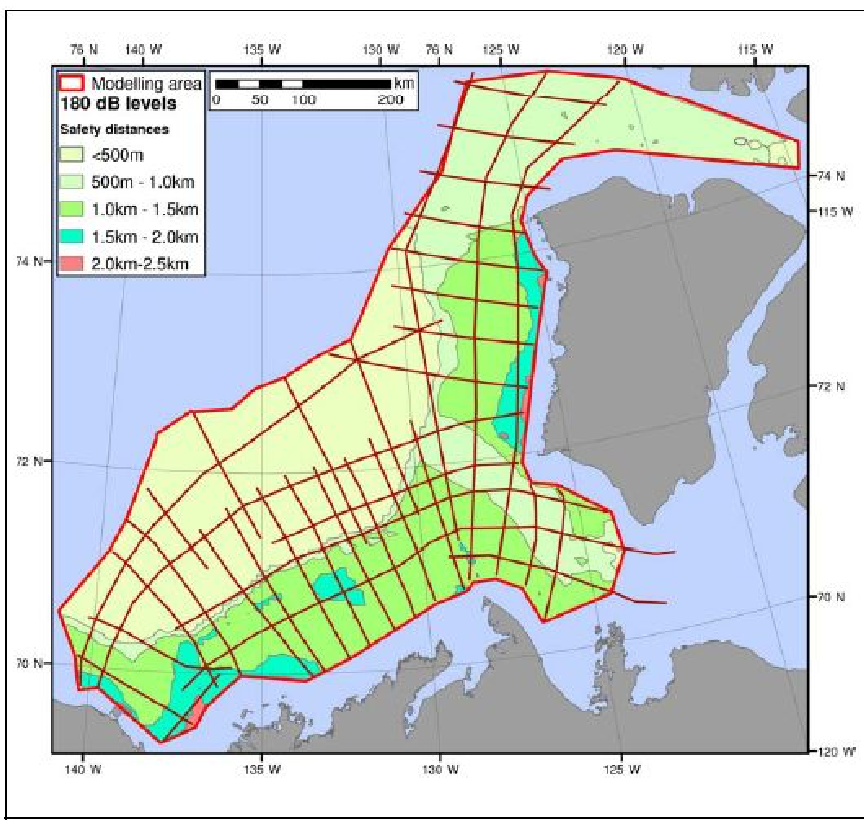

Figure 2. Modelled 180 dB re µPa rms safety radii for the geophysical survey project to be conducted in 2009 as part of the Beaufort Span phase 2 survey (from LGL Limited, Env. Res. Assoc. 2008).

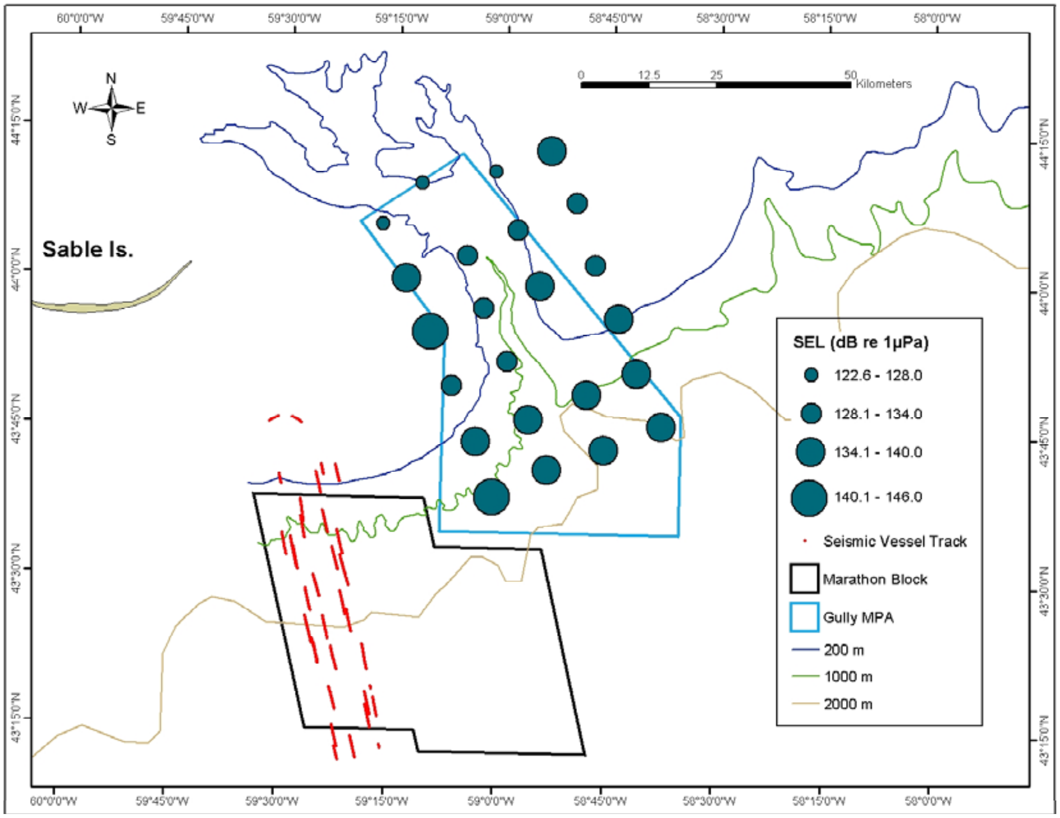

Figure 3. Geographical variation in measured average sound exposure levels (dB re 1 μPa) of seismic pulses (10-1000 Hz) emanating from within the Marathon Block in 2003. Data from COOGER Gully Project (McQuinn et al. 2004).

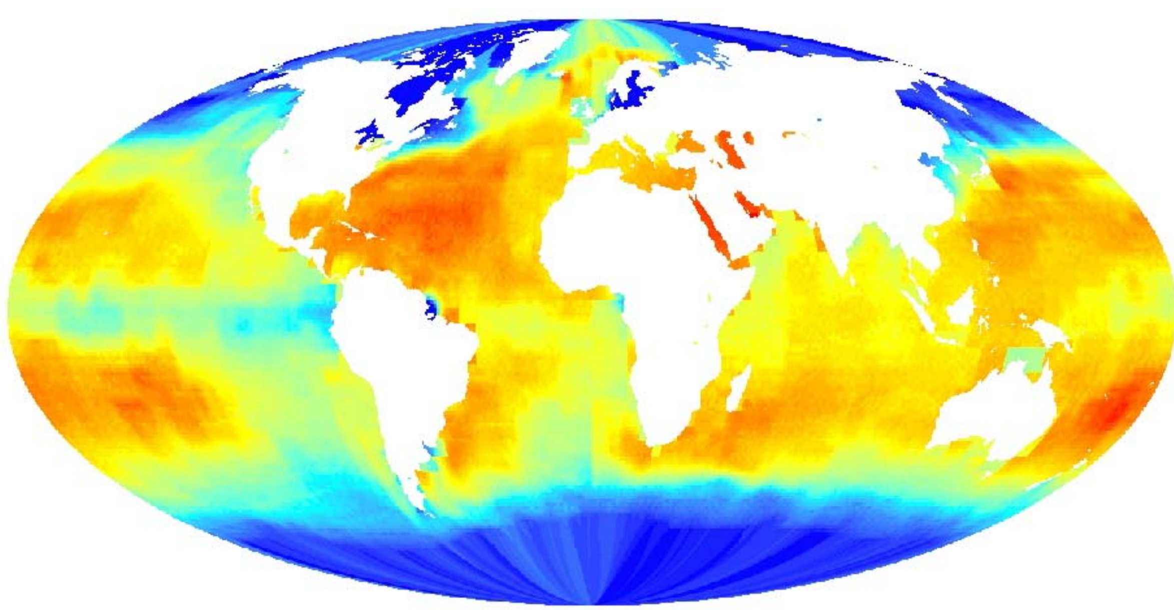

Figure 4. Predicted increases in ocean acidification, with brighter colours denoting larger values. Source http://ebm.nceas.ucsb.edu/GlobalMarine/impacts/transformed/jpg/ocean_acidification.jpg.