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Risk Assessment of Permanent Auditory Injury in Marine Mammals: Differences Arising from the Application of the Southall and NOAA Criteria

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Executive Summary

This report investigates the differences between two sets of marine mammal noise exposure criteria in the prediction of permanent auditory injury in marine mammals: the Southall criteria, published in 2007 and the NOAA criteria (also known as the NMFS criteria), published in 2016. Both have been widely adopted in the UK and beyond, with the NOAA criteria considered as the most up-to-date scientific approach. This has created a need among regulators and their advisors for scientific advice on the quantitative differences resulting from the application of each set of criteria, and the reasons underpinning those differences in order to understand these differences in legacy assessments consented under Southall and now being re-assessed under NOAA.

Since there are differences between the criteria in both the cumulative noise exposure thresholds and the auditory weightings (which account for frequency sensitivity in marine mammal hearing), the interplay between these two factors is important.

Cefas has undertaken an analysis and modelling exercise which applied both criteria to representative noise assessment scenarios for UK waters. The aims were:

(i) investigate which set of criteria are more precautionary for each marine mammal hearing group;
(ii) investigate whether there are consistent differences in the effect ranges and effect areas predicted for permanent auditory injury, known as Permanent Threshold Shift (PTS).

The noise assessment scenarios consisted of four typical noise sources: percussive pile driving, seismic airguns, explosions, and vibratory pile driving, which were each modelled in representative environments.

- In general, the NOAA criteria were found to be consistently more precautionary than Southall criteria for low frequency cetaceans (baleen whales) and for high-frequency cetaceans (including the harbour porpoise);
- For phocid pinnipeds (including grey and harbour seals) NOAA criteria are the same as the Southall criteria for the peak Sound Pressure Level (SPL) criterion, and consistently less precautionary for the impulsive and non-impulsive cumulative Sound Exposure Level (SEL) criteria;
- For mid-frequency cetaceans (including dolphin species) NOAA criteria were either equivalent or less precautionary, except in the case of vibratory pile driving, a result which is not expected to apply to other non-impulsive low-frequency sources, such as drilling, shipping, or dredging.

In addition to reporting quantitative differences between the criteria in the scenarios assessed, the differences in effect ranges and effect areas predicted by the criteria were analysed. The resulting figures included in this report provide guidance on the likely effect ranges and effect areas that would be predicted under one set of criteria based on the predictions for the other criteria (according to the scenarios which were modelled). These results can assist developers, regulators, and their advisors in interpreting differences in predictions between the criteria and in anticipating the likely effect of applying a different set of criteria based on existing predictions.

Caution should be exercised to avoid applying these results too widely or with unwarranted precision: the absolute decibel differences between the criteria reported herein should be broadly similar for other similar environments and sources, but variability should be expected according to the specifics of any particular modelling scenario assessed.

Introduction

Marine mammal noise exposure criteria (also known as noise thresholds or impact criteria) define the levels of sound at which various severities of responses in marine mammals are expected, for example, permanent or temporary loss in hearing sensitivity (Permanent Threshold Shift, PTS or Temporary Threshold Shift, TTS). Such criteria are applied in environmental impact assessments (EIAs) for underwater noise to predict the possible extent of adverse effects on marine mammals.

Marine mammal noise exposure criteria were first developed by the US National Marine Fisheries Service (NMFS) (part of the National Oceanic and Atmospheric Administration (NOAA)) in the late 1990s. The criteria consisted of two generic thresholds for assessing auditory injury (e.g. onset of PTS) in marine mammals exposed to multiple pulsed sounds, defined using the root-mean-square sound pressure level: one for pinnipeds (180 dB re 1 µPa) and one for cetaceans (190 dB re 1 µPa). These thresholds were set by NMFS using the best available (though limited) data at that time (e.g. HESS 1999; see Southall et al. 2007; NMFS 2016).

In 2007, the first detailed marine mammal noise exposure criteria were published by Southall and colleagues (hereafter the Southall criteria), following a review of the growing literature on marine mammal noise exposure studies (Southall *et al.* 2007). This review provided guidance on the weighted sound levels above which exposure was expected to cause auditory injury, for various marine mammal groups and sound types. This work has been very influential and has formed the basis of many EIAs, both in the UK and worldwide, since its publication.

Following the Southall criteria publication, NMFS has since issued updated criteria (hereafter the NOAA criteria) for acoustic threshold levels for the onset of PTS and TTS for marine mammals exposed to acute anthropogenic noise (NMFS 2016), based on an extensive peer-review exercise, and three public (including stakeholder) consultation periods. Previous draft versions were released in 2013 and 2015. The NOAA guidance reflects the advances made by the Southall et al. (2007) review but also includes more recent studies, e.g. data on TTS in harbour porpoises (Lucke *et al.* 2009).

Consequently, regulators and their advisors currently have two sets of marine mammal noise exposure criteria to consider: Southall and NOAA. This can raise difficulties particularly when legacy assessments consented on one set of criteria are now being reviewed with different criteria. The overall aim of this report is to enable a better understanding of the differences that should be expected between these two criteria by comparing them using representative EIA scenarios commonly occurring in UK waters.

Aims and Scope

The primary aim of this report is to compare the application of the Southall criteria and the NOAA criteria in representative EIA scenarios in the UK. The approach taken was twofold: first, to compare the application of the criteria at source for typical noise sources assessed in UK waters, and second, to assess the effect of sound propagation on these differences with range from the source, using acoustic modelling.

Comparative analysis was conducted by quantifying the differences in the prediction of permanent auditory injury, termed permanent threshold shift (PTS), under each set of criteria. These differences result from: (i) differences in the noise exposure thresholds defined for the onset of PTS; and (ii) differences in the auditory weightings applied in the assessment of cumulative exposure to noise.

The aim of the comparative analysis was to identify the relative generic differences from each set of criteria in the prediction of PTS impact, for each marine mammal functional hearing group.

Additionally, variability in the quantitative differences between the criteria was investigated for the scenarios modelled. Finally, to assist practitioners in understanding the likely consequences of applying an alternative set of criteria, an analysis was conducted which provides examples on effect ranges and effect areas which would be predicted under the alternative criteria (e.g. given an effect range modelled under the Southall criteria, what is the approximate range that should be expected for the same scenario under the NOAA criteria).

What this report does not do is review the rationale behind each set of criteria: it is only concerned with differences arising from the application of each set of criteria.

The Criteria: Functional Hearing Groups, Auditory Weightings and Thresholds

Functional Hearing Groups

The Southall and NOAA criteria divide marine mammals into functional hearing groups to reflect the broad differences in hearing capabilities among marine mammal taxa (Table 1). In Southall, these groups are: low-frequency cetaceans; mid-frequency cetaceans; high-frequency cetaceans; pinnipeds in water and pinnipeds in air (latter not shown in Table 1).

The NOAA criteria use very similar hearing groups for cetaceans but subdivide pinnipeds in water into two constituent taxa: phocid pinnipeds (true seals) and otariid pinnipeds (sea lions and fur seals). For pinnipeds, the scope of this report is limited to phocid pinnipeds in water, and so the other pinniped categories have been omitted hereafter. The NOAA criteria has also updated the generalised hearing range for each group, except for mid-frequency cetaceans (Table 1). Additionally, some mid-frequency cetacean species (hourglass (*Lagenorhynchus cruciger*) and Peale's (*L. australis*) dolphins) have been re-categorised into the high-frequency cetacean hearing group (neither species is present in UK waters).

Table 1

Functional marine mammal hearing groups and estimated auditory bandwidth, adapted from Southall et al. (2007) and NOAA (NMFS 2016).

Marine Mammal Hearing Group	Generalised Hearing Range according to Southall et al. (2007)	Generalised Hearing Range according to NOAA (NMFS 2016)
Low-frequency cetaceans	7 Hz to 22 kHz	7 Hz to 35 kHz
Mid-frequency cetaceans	150 Hz to 160 kHz	150 Hz to 160 kHz
High-frequency cetaceans	200 Hz to 180 kHz	275 Hz to 160 kHz
Pinnipeds (in water)	75 Hz to 75 kHz	
Phocid pinnipeds (in water)		50 Hz to 86 kHz

Auditory Weightings

To account for the frequency sensitivity of hearing for each functional hearing group, both criteria require the application of an auditory weighting (termed "M-weighting" in Southall *et al.*, 2007). The auditory weighting is effectively a frequency filter designed to approximate the likely hearing sensitivity of animals within each functional hearing group. Auditory weightings are applied by addition to the frequency spectrum of the sound considered (since the weighting is negative, this means subtracting energy from the sound spectrum). In general, when comparing auditory weightings, if the auditory weighting removes less sound energy, then it is more precautionary, and vice versa. Comparison of auditory weightings between the two criteria, as presented in Figure 1, indicates that for all functional hearing groups (including otariid pinnipeds which are not shown), the NOAA weighting removes more sound energy, particularly at low frequencies. Therefore, in order to compensate for the additional sound energy removed, the NOAA criteria would need to have lower sound level thresholds than the Southall criteria to attain the same effective threshold (since the weighted sound levels will be lower). However, since the weightings differ from each other in the frequency domain (Figure 1), the weighted levels from the Southall and NOAA weightings will vary depending on the frequency characteristics of the sound spectrum considered. For this reason, to evaluate differences between criteria for the cumulative Sound Exposure Level (SEL) thresholds (for which weightings are applied), it is necessary to consider concrete scenarios of noise exposure with specific sound sources (e.g. percussive and vibratory pile driving, seismic airguns, explosions).

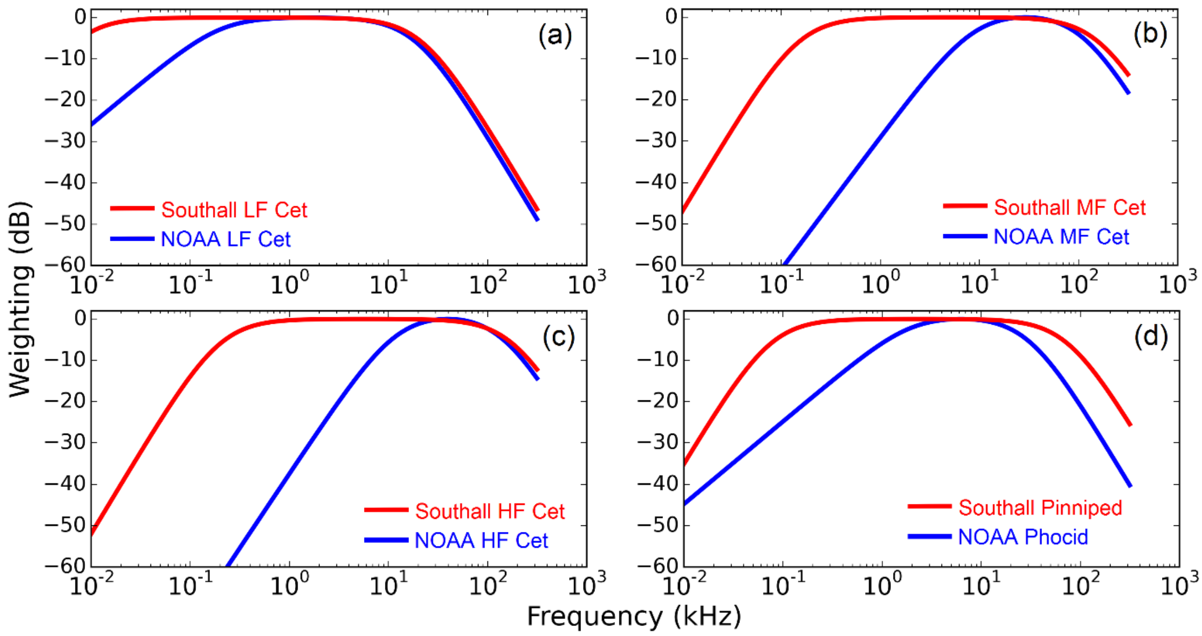

Figure 1: Auditory weightings for the Southall and NOAA criteria for four functional hearing groups: (a) Low-frequency cetaceans; (b) Mid-frequency cetaceans; (c) High-frequency cetaceans; (d) Phocid seals (NOAA) and all pinnipeds (Southall) in water.

Thresholds

The Southall and NOAA criteria (shown in Table 2 and Table 3, respectively) divide sound sources into two categories based on their potential to affect marine mammal hearing sensitivity:

- Impulsive sound sources e.g. impact pile drivers, seismic airguns. These sources are transient, brief, (less than one second), broadband, and typically consist of high peak pressure with rapid rise time and rapid decay (NMFS 2016). Based on studies of the mammalian auditory system, impulsive sounds have a greater potential to affect hearing sensitivity.

- Non-impulsive sound sources e.g. vibratory pile drivers, drilling, shipping. These sources can be broadband (i.e. extending across a wide range of frequencies), narrowband or tonal, brief or prolonged, continuous or intermittent and typically do not have a high peak pressure with rapid rise time (NMFS 2016).

Accordingly, the criteria have separate thresholds for impulsive and non-impulsive sounds. It should be noted that the Southall criteria define impulsive sources as 'single' or 'multiple pulses' and non-impulsive sources as 'non-pulses'.

Table 2

Southall noise exposure criteria for Permanent Threshold Shift (PTS) and Temporary Threshold Shift (TTS). Note that all SEL criteria are weighted and expressed in units of dB re 1 µPa^{2}s, all peak SPL criteria are unweighted and expressed in dB re 1 µPa.

Functional Hearing Group	Single and Multiple Pulses				Non-Pulses			
	TTS		PTS		TTS		PTS	
	SEL	Peak SPL	SEL	Peak SPL	SEL	Peak SPL	SEL	Peak SPL
Low-frequency cetaceans	183	224	198	230	195	224	215	230
Mid-frequency cetaceans	183	224	198	230	195	224	215	230
High-frequency cetaceans	183	224	198	230	195	224	215	230
Pinnipeds (in water)	171	212	186	218	183	212	203	218

Table 3

NOAA noise exposure criteria for Permanent Threshold Shift (PTS) and Temporary Threshold Shift (TTS). Note that all SEL criteria are weighted and are expressed in units of dB re 1 µPa^{2}s, all peak SPL criteria are unweighted and expressed in dB re 1 µPa.

Functional Hearing Group	Impulsive				Non-Impulsive	
	TTS		PTS		TTS	PTS
	SEL	Peak SPL	SEL	Peak SPL	SEL	SEL
Low-frequency cetaceans	168	213	183	219	179	199
Mid-frequency cetaceans	170	224	185	230	178	198
High-frequency cetaceans	140	196	155	202	153	173
Otariid pinnipeds (in water)	188	226	203	232	199	219
Phocid pinnipeds (in water)	170	212	185	218	181	201

The Southall and NOAA criteria are both dual criteria: thresholds for the onset of PTS and TTS are defined for: (i) the peak sound pressure level (peak SPL) which is unweighted; and (ii) the cumulative sound exposure level (cumulative SEL) which is weighted for each functional hearing group. PTS is predicted to be incurred if either criterion is met. The cumulative sound exposure integrates the sound energy over a maximum exposure period of 24 hours. It should be noted that for non-impulsive sounds, only the cumulative SEL is provided in the NOAA criteria, as shown in Table 3.

For the peak SPL assessment, no frequency weighting is applied to the sound levels, and so the differences between the criteria depend only on the differences between the thresholds. Guidance is provided herein as to how these differences in thresholds affect the comparative ranges and effect areas predicted for PTS under the peak SPL criterion.

For the cumulative SEL assessment, both criteria require the application of a frequency weighting for the relevant functional hearing group. These auditory weightings make interpreting differences between the cumulative SEL criteria more complicated as there are two interacting factors to consider: first, the auditory weightings for each functional hearing group and second, the weighted SEL thresholds at which the effect (in this case PTS) is predicted to occur.

Comparison of Criteria for Different Source Types

To understand how the criteria differ according to the spectral characteristics of typical noise sources, we applied them to source spectra of several typical noise sources assessed in UK waters: percussive pile driving, seismic airguns, explosions, and vibratory pile driving. Although in practice the criteria are assessed at distance from the source, here we first consider how differences in source characteristics lead to differences in assessment under each set of criteria, to separate this factor from the effects of sound propagation (considered in the next section). The source types and reference literature are given in Table 4. Since we are focusing on the differences between the criteria, rather than the absolute sound levels that might be predicted in any particular case, the specific source levels used are not relevant to the results presented here.

Table 4

Source types assessed and associated scientific literature.

Noise Source	**Source Type**	**Source Model or Measurements**	**Reference**
Percussive pile driving	Impulsive	Source model (validated by Cefas in Scottish waters)	Ainslie *et al.* (2012)
Seismic airgun array	Impulsive	Source model	Erbe & King (2009)
Exploding charge mass	Impulsive	Source model	Soloway & Dahl (2014)
Vibratory pile driving	Non-impulsive	Measurements on Scottish east coast	Graham *et al.* (2017)

Following discussion with the steering group, we assessed vibratory pile driving according to the criteria for non-impulsive sound. However, it should be noted that the sound pressure waveform presented in the source study for the data presented here (Graham *et al.* 2017) could be described as impulsive, and it remains an open question as to which category vibratory pile driving should be assessed under, impulsive or non-impulsive. Furthermore, unlike other low-frequency non-impulsive sound sources (such as shipping, drilling, and dredging), the source spectrum of vibratory pile driving measured by Graham *et al.* (2017) has greatest energy at mid-frequency (1-10 kHz; Figure 2d). For these reasons, vibratory pile driving was not considered representative of other non-impulsive sound sources.

The following figures and tables present the differences between the weighted sound spectra and the criteria for PTS, as assessed at source. Note that, except for the peak SPL criterion, the results also apply to the assessment of TTS, since the differences between the TTS and PTS thresholds for cumulative SEL are consistent.

Throughout this report, we have adopted a consistent sign convention for reporting differences between the criteria: **where differences are reported in decibels, negative decibel values indicate that the NOAA criteria are more precautionary (i.e. would predict larger effect zones for the same scenario compared to the Southall criteria), and vice versa. Tables are also colour coded to this effect: blue indicates NOAA criteria are more precautionary, red indicates Southall are more precautionary.**

Low-Frequency Cetaceans

For all three cetacean functional hearing groups, the Southall and NOAA auditory weightings differ significantly only at low frequencies (see Figure 1a for low-frequency cetaceans). This is also apparent in the deviation between the weighted levels in the source spectra (Figure 2). The differences between the broadband weighted levels, therefore, depend on the extent to which low frequencies dominate the sound spectrum. All three impulsive sources (Figure 2 a-c) have energy focused at low frequencies to varying degrees, leading to differences in weighted levels of 3.4-13.2 dB, while the vibratory pile driving spectrum (Figure 2 d) is more evenly spread across frequency, and so has the least disparity in weighted levels (0.5 dB). Since the Southall weightings remove less sound energy (for all functional hearing groups), the Southall weighted levels are higher than the NOAA weighted levels in all cases.

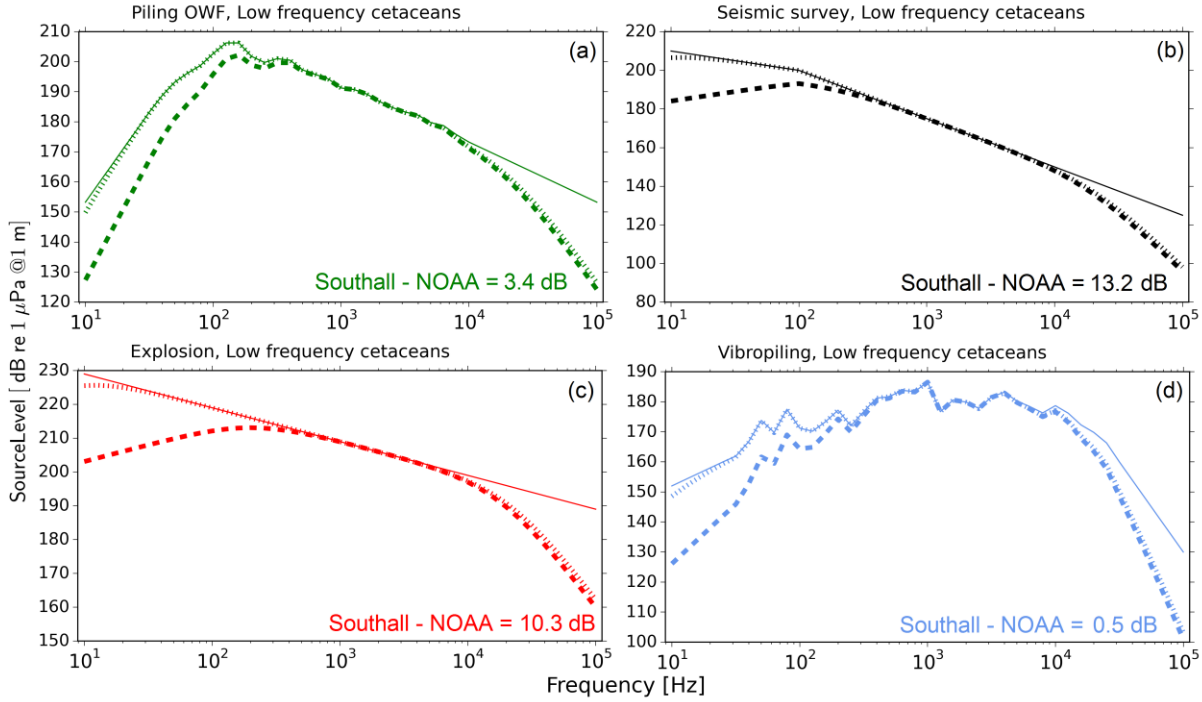

Figure 2: Generic source spectra for four representative sources with weightings for low-frequency cetaceans. Unweighted (solid line), Southall M-weighted (thin dashed line), and NOAA-weighted (thick dashed line). The unweighted spectrum shows the “true” sound, while the NOAA and Southall weighted spectra more closely reflect the risk of auditory damage for each hearing group.

Taking into consideration the differences in criteria arising from both (i) the differing auditory weightings; and (ii) the differing PTS thresholds, we can assess the overall differences (here termed *adjusted differences*) between the criteria in decibels for the sources shown (Table 5). For the impulsive sound sources, the adjusted differences ranged from -11.6 to -1.8 dB, meaning the NOAA criteria were more precautionary, and similarly for the non-impulsive source (vibratory pile driving), the adjusted difference was -15.5 dB. For the peak SPL criterion (which is unweighted), by simple arithmetic the difference is -11 dB. In summary, for all cases considered, the NOAA criteria are more precautionary.

Table 5

Differences between criteria at source for low-frequency cetaceans. Negative dB differences indicate NOAA criteria are more precautionary than Southall criteria, and vice versa. Note that peak SPL differences are exact (since there is no weighting applied, they are a direct comparison of the thresholds), whereas cumulative SEL differences are example estimates based on the source spectra presented in the text. Blue shading indicates NOAA is more precautionary, red shading indicates the opposite.

	Southall	**NOAA**	**Difference (dB)**
Peak SPL Threshold for PTS	**230**	**219**	**-11**
Cumulative SEL PTS Threshold Impulsive	*198*	*183*	*-15*
Cumulative SEL Weighting	*Figure 2(a-c)*	*Figure 2(a-c)*	*3.4 to 13.2*
Cumulative SEL Total Adjusted Difference Impulsive			**-11.6 to -1.8**
Cumulative SEL PTS Threshold Non-Impulsive	*215*	*199*	*-16*
Cumulative SEL Weighting	*Figure 2(d)*	*Figure 2(d)*	*0.5*
Cumulative SEL Total Adjusted Difference Non-Impulsive			**-15.5**

Mid-Frequency Cetaceans

The differences between the mid-frequency cetacean weightings (Figure 1b) are greater at low frequencies than for the low-frequency cetacean group, leading to greater differences in the weighted levels (Figure 3) than for low-frequency cetaceans. The vibratory piling spectrum resulted in the least difference as this spectrum has a higher proportion of energy at higher frequencies.

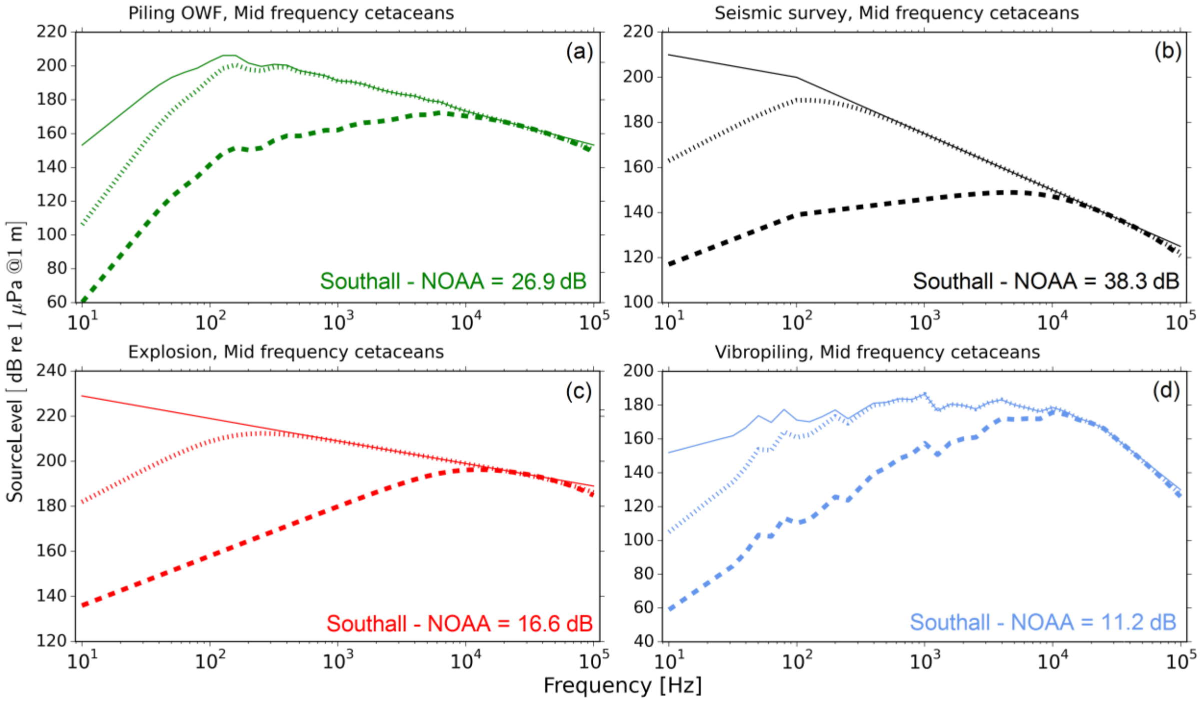

Figure 3: Generic source spectra for four representative sources with weightings for mid-frequency cetaceans. Unweighted (solid line), Southall M-weighted (thin dashed line), and NOAA-weighted (thick dashed line). The unweighted spectrum shows the "true" sound, while the NOAA and Southall weighted spectra more closely reflect the risk of auditory damage for each hearing group.

The peak SPL criterion is the same for the Southall and NOAA criteria, resulting in zero difference (Table 6). For the impulsive cumulative SEL criteria, the NOAA threshold is 13 dB lower than the Southall threshold, which does not compensate for the greater proportion of sound energy removed by the NOAA weighting in the examples assessed (Figure 3 a-c), of between 16.6 and 38.3 dB. The adjusted differences were, therefore, 3.6 to 25.3 dB, meaning that the NOAA criteria were less precautionary than the Southall criteria for cumulative exposure to impulsive sound. For cumulative SEL from non-impulsive sound, the NOAA threshold is 17 dB lower, but for the vibropiling spectrum the difference in weighted levels was only 11.2 dB, meaning the NOAA criteria were more precautionary, with an adjusted level of -5.8 dB. However, this result for non-impulsive sound may not apply to other non-impulsive sounds which may have a greater proportion of sound energy at low frequencies, such as drilling, dredging, or shipping.

Table 6

Differences between criteria at source for mid-frequency cetaceans. Negative dB differences indicate NOAA criteria are more precautionary than Southall criteria, and vice versa. Note that peak SPL differences are exact (since there is no weighting applied, they are a direct comparison of the thresholds), whereas cumulative SEL differences are example estimates based on the source spectra presented in the text. Blue shading indicates NOAA is more precautionary, red shading indicates the opposite.

	Southall	NOAA	Difference (dB)
Peak SPL Threshold for PTS	**230**	**230**	**0**
Cumulative SEL PTS Threshold Impulsive	*198*	*185*	*-13*
Cumulative SEL Weighting	*Figure 3(a-c)*	*Figure 3 (a-c)*	*16.6 to 38.3*
Cumulative SEL Total Adjusted Difference Impulsive			**3.6 to 25.3**
Cumulative SEL PTS Threshold Non-Impulsive	*215*	*198*	*-17*
Cumulative SEL Weighting	*Figure 3(d)*	*Figure 3(d)*	*11.2*
Cumulative SEL Total Adjusted Difference Non-Impulsive			**-5.8**

High-Frequency Cetaceans

The differences in weighted levels were slightly greater for high-frequency cetaceans (Figure 4) than for mid-frequency cetaceans (Figure 3). However, the differences between the thresholds are much greater, with the NOAA thresholds lower by 28 dB for peak SPL, 43 dB for impulsive cumulative SEL, and 42 dB for cumulative non-impulsive SEL (Table 7). These lower thresholds more than compensated for the lower weighted levels, resulting in adjusted levels of -25.9 to -1.9 (impulsive) and -28.0 (non-impulsive), meaning the NOAA criteria were more precautionary than the Southall criteria in all cases for high-frequency cetaceans.

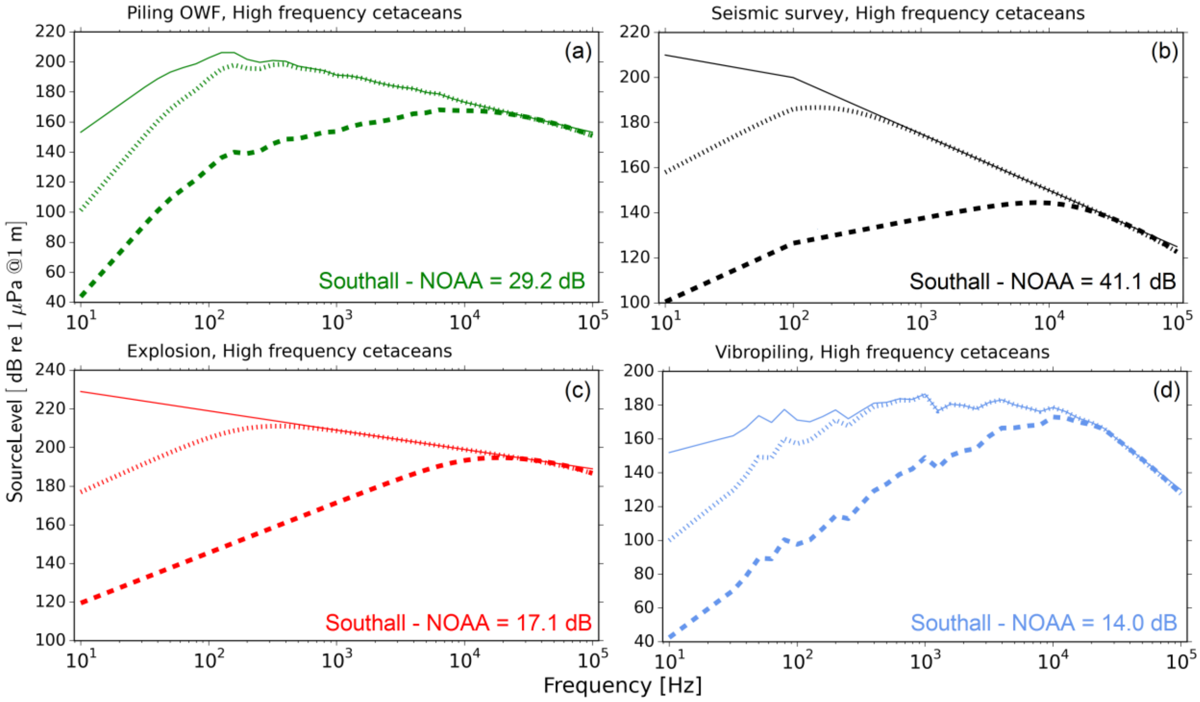

Figure 4: Generic source spectra for four representative sources with weightings for high-frequency cetaceans. Unweighted (solid line), Southall M-weighted (thin dashed line), and NOAA-weighted (thick dashed line). The unweighted spectrum shows the "true" sound, while the NOAA and Southall weighted spectra more closely reflect the risk of auditory damage for each hearing group.

Table 7

Differences between criteria at source for high-frequency cetaceans. Negative dB differences indicate NOAA criteria are more precautionary than Southall criteria, and vice versa. Note that peak SPL differences are exact (since there is no weighting applied, they are a direct comparison of the thresholds), whereas cumulative SEL differences are example estimates based on the source spectra presented in the text. Blue shading indicates NOAA is more precautionary, red shading indicates the opposite.

	Southall	**NOAA**	**Difference (dB)**
Peak SPL Threshold for PTS	**230**	**202**	**-28**
Cumulative SEL PTS Threshold Impulsive	*198*	*155*	*-43*
Cumulative SEL Weighting	*Figure 4(a-c)*	*Figure 4(a-c)*	*17.1 to 41.1*
Cumulative SEL Total Adjusted Difference Impulsive			**-25.9 to -1.9**
Cumulative SEL PTS Threshold Non-Impulsive	*215*	*173*	*-42*
Cumulative SEL Weighting	*Figure 4(d)*	*Figure 4(d)*	*14.0*
Cumulative SEL Total Adjusted Difference Non-Impulsive			**-28.0**

Phocids

At low frequencies, the weightings for phocid seals are intermediate between the low-frequency cetacean and mid-frequency cetacean weightings in the amount of sound energy removed (Figure 1 d). This is reflected in the difference values between the weighted levels as shown in Figure 5.

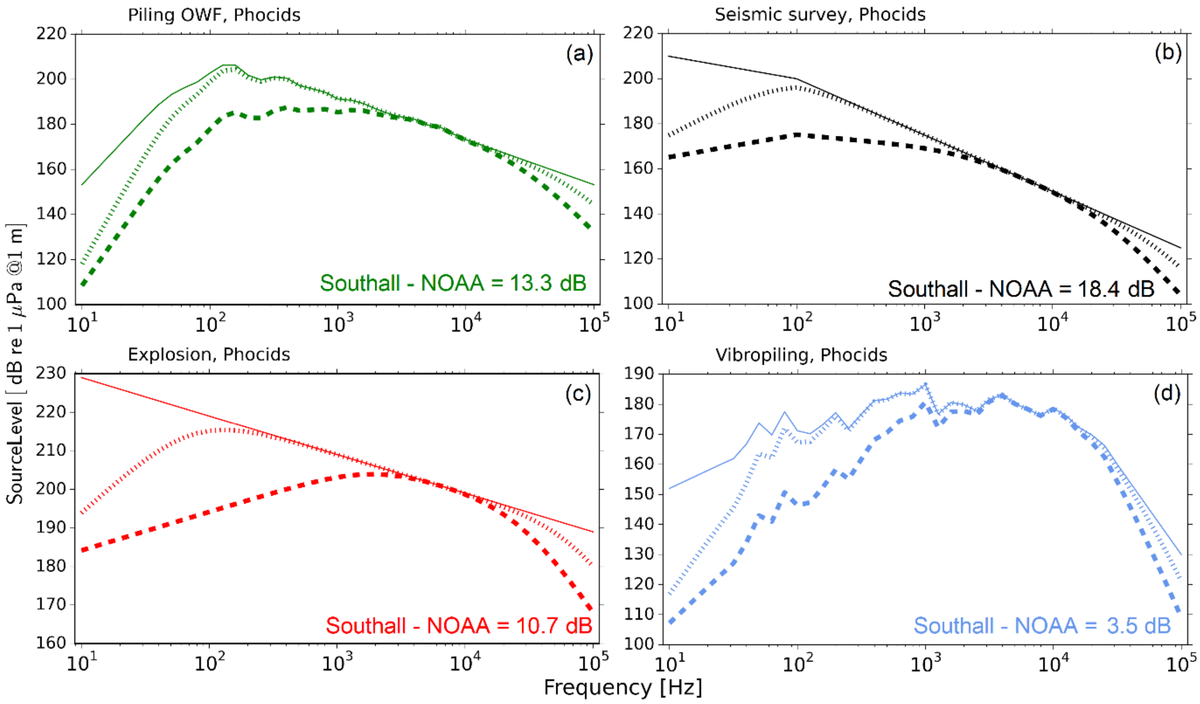

Figure 5: Generic source spectra for four representative sources with weightings for high-frequency cetaceans. Unweighted (solid line), Southall M-weighted (thin dashed line), and NOAA-weighted (thick dashed line). The unweighted spectrum shows the "true" sound, while the NOAA and Southall weighted spectra more closely reflect the risk of auditory damage for each hearing group.

For peak SPL, the PTS thresholds are the same, and so the difference is 0 dB (Table 8). For the cumulative SEL criteria for impulsive sound, the NOAA threshold is 1 dB lower than the Southall threshold, which does not compensate for the sound energy lost by the frequency weighting, meaning that the adjusted levels are positive (i.e. NOAA is less precautionary) with values of 9.7 to 17.4 dB. For non-impulsive cumulative SEL, the NOAA threshold is 2 dB lower, but the NOAA weighting removed 3.5 dB, resulting in a net positive adjusted difference of 1.5 dB (which means that NOAA is less precautionary).

Table 8

Differences between criteria at source for phocid pinnipeds. Negative dB differences indicate NOAA criteria are more precautionary than Southall criteria, and vice versa. Note that peak SPL differences are exact (since there is no weighting applied, they are a direct comparison of the thresholds), whereas cumulative SEL differences are example estimates based on the source spectra presented in the text. Blue shading indicates NOAA is more precautionary, red shading indicates the opposite.

	Southall	**NOAA**	**Difference (dB)**
Peak SPL Threshold for PTS	**218**	**218**	**0**
Cumulative SEL PTS Threshold Impulsive	*186*	*185*	*-1*
Cumulative SEL Weighting	*Figure 5(a-c)*	*Figure 5(a-c)*	*10.7 to 18.4*
Cumulative SEL Total Adjusted Difference Impulsive			**9.7 to 17.4**
Cumulative SEL PTS Threshold Non-Impulsive	*203*	*201*	*-2*
Cumulative SEL Weighting	*Figure 5(d)*	*Figure 5(d)*	*3.5*
Cumulative SEL Total Adjusted Difference Non-Impulsive			**1.5**

Criteria Differences at Source: Summary

The results of the example scenarios assessed for each functional hearing group are summarised in Table 9. All of the peak SPL thresholds in the NOAA criteria are the same or more precautionary than the Southall criteria. For low-frequency cetaceans and high-frequency cetaceans, the NOAA cumulative SEL criteria are more precautionary for both impulsive and non-impulsive sounds, while the opposite was the case for phocid seals. The mid-frequency cetacean results were less precautionary under the NOAA criteria for impulsive sound, and more precautionary for non-impulsive sound.

Table 9

Summary of dB differences between criteria at source, where negative values indicate NOAA criteria are more precautionary than Southall criteria, and vice versa. Note that peak SPL differences are exact (since there is no weighting applied, they are a direct comparison of the thresholds), whereas cumulative SEL differences are example estimates based on the source spectra presented in the text. Blue shading indicates NOAA is more precautionary, red shading indicates the opposite.

	Low-Frequency Cetaceans	Mid-Frequency Cetaceans	High-Frequency Cetaceans	Phocid
Peak SPL Threshold for PTS	-11	0	-28	0
Cumulative SEL Impulsive	-11.6 to -1.8	3.6 to 25.3	-25.9 to -1.9	9.7 to 17.4
Cumulative SEL Non-Impulsive	-15.5	-5.8	-28.0	1.5

Changes in Criteria Differences with Range from the Source

This section assesses how the differences between the cumulative SEL criteria observed at source (see previous section) might vary depending on sound propagation. These effects are significant since in practice, the criteria are applied to received sound levels predicted by sound propagation modelling at some distance from the source.

To examine these effects, representative modelling scenarios were defined for each of the four source types assessed in the previous section, resulting in eight modelling scenarios as specified in Table 10. Percussive pile driving was considered for scenarios typical of offshore wind farm construction in the northern North Sea (NNS; Scenario 1), and southern North Sea (SNS; Scenario 2), and for inshore works such as port developments (Scenario 3). Vibratory piling was also assessed as an inshore activity (Scenario 4). Detonation of unexploded ordnance was modelled for both NNS and SNS (Scenarios 5 and 6), while seismic airguns were assessed for NNS (Scenario 7) and the Northeast Atlantic (NEA; Scenario 8).

Source levels were modelled as shown in the unweighted source spectra in Figure 2, except in the case of inshore percussive piling where a lower hammer energy was used (200 kJ rather than 3,000 kJ), corresponding to the same spectral shape as shown in Figure 2(a) but with reduced magnitude.

Sound propagation was modelled using the environmental parameters given in Table 10. An energy flux model was used (Weston 1971) for computational efficiency.

Range Dependence of dB Differences Between Criteria

The variation in the differences between the cumulative SEL criteria with range from source is shown in Figure 6***Figure 6***. In all cases, the criteria differences vary with range from source. This occurs because the frequency composition of the sound spectrum is altered by propagation, since the effects of propagation loss (the sound energy lost as sound disperses in the environment) are frequency dependent.

Note that for the peak SPL criteria, the range-dependent plots would appear as horizontal lines: since there is no weighting applied to the sound levels for this criterion, the decibel difference between the criteria depends only on the (constant) difference between the thresholds. The values of the criteria differences at a range of 0 km (Figure 6) correspond to the differences reported in Table 9.

Table 10

Scenario specification for assessment of criteria differences at source and with propagation: Noise source properties assessed and modelled environment characteristics. Acoustic properties of sediment type were derived from Jensen *et al.* (2011).

Scenario	Source Type	Source Data	Temporal Properties for 24-h SEL_{cum}	Typical Location	Water Depth	Sediment Type	Season	Scenario Number
Pile driving Offshore Wind Farm (OWF)	Percussive pile driving hammer 3,000 kJ	Source model (validated by Cefas in Scottish waters): Ainslie *et al.* (2012)	Typical monopile hammer energy profile including ramp-up, 2 piles in 24-h	Northern North Sea	50 m at source, sloping to 100 m at 100 km	Sand	Year round	**1**
				Southern North Sea	30 m flat bottom	Sand	Year round	**2**
Pile driving inshore port works	Percussive pile driving (200 kJ inferred by Nigg piling study; 200 dB @1m)	Source model (validated by Cefas in Scottish waters): Ainslie *et al.* (2012)	Four hours of piling (during daylight), repetition rate: 1 strike per second (from Nigg study)	Scottish coast	10 m at source, sloping to 70 m at 100km range	Gravelly sand	Year round	**3**
	Vibratory pile driving	Measurements on Scottish coast: Graham *et al.* (2017)	Four hours of piling (during daylight)	Scottish coast	10 m at source, sloping to 70 m at 100km range	Gravelly sand	Year round	**4**
Unexploded Ordnance (UXO) detonation	Exploding charge mass; 250 kg	Empirical source model: Soloway & Dahl (2014)	One event in 24 hours	Northern North Sea	60 m, flat bottom	Sand	Year round	**5**
				Southern North Sea	30 m flat bottom	Sand	Year round,	**6**
Seismic survey	Seismic airgun array	Source model: Erbe & King (2009)	24-h operation, 8-second shot interval	Northern North Sea	80 m, flat bottom	Sand	Year round	**7**
				North-East Atlantic	150 m, flat bottom	Gravelly sand	Year round	**8**

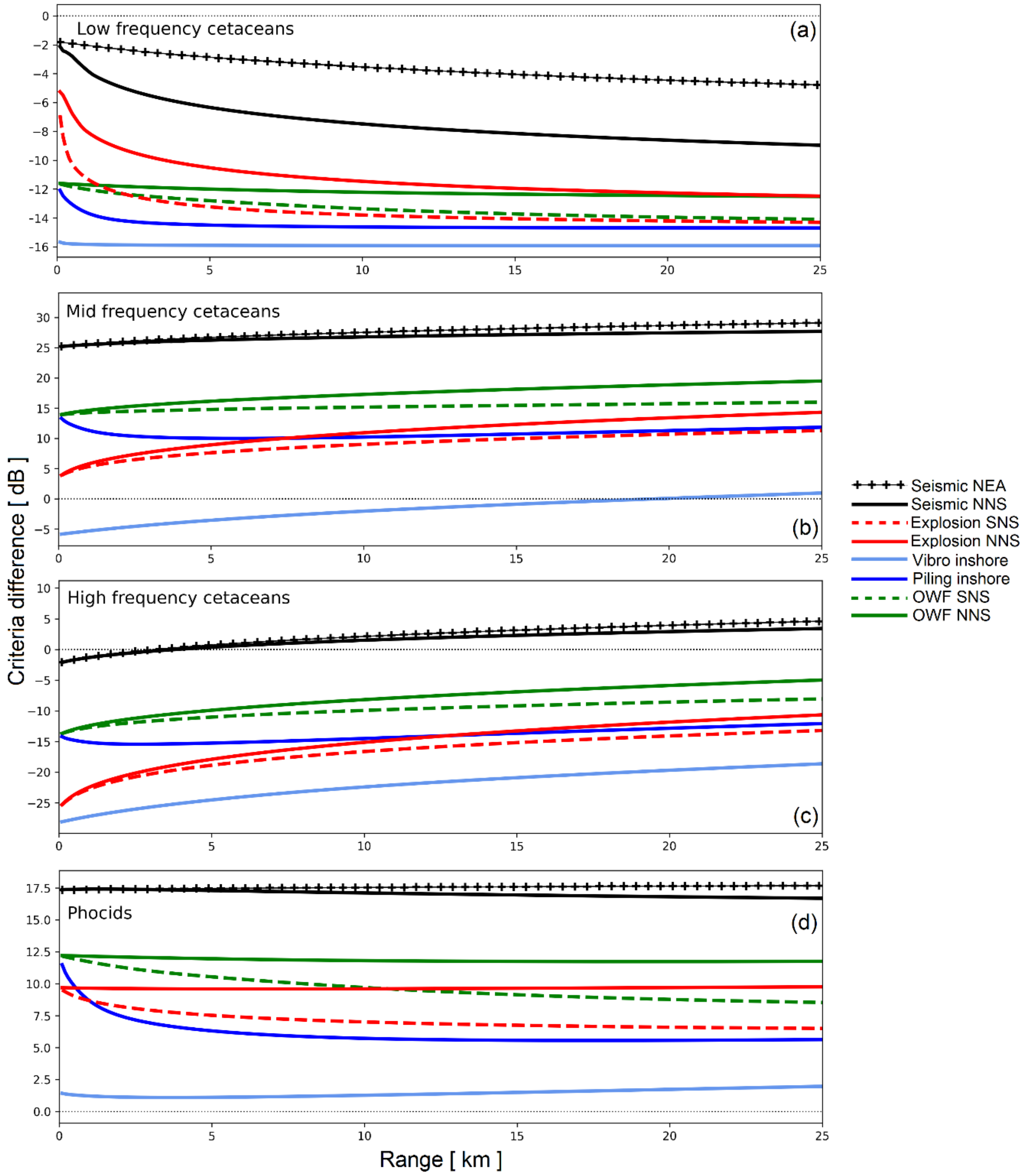

Figure 6: Differences between the SEL cumulative criteria with range from source, based on modelling scenarios described in the text. Negative values indicate NOAA criteria are more precautionary than Southall criteria, and vice versa. NEA = Northeast Atlantic; NNS = Northern North Sea; SNS = Southern North Sea; OWF = offshore wind farm.

Differences in Ranges and Areas Predicted Under Each Set of Criteria

Model predictions for noise assessment in EIAs are often reported in terms of *effect ranges* – the distance at which an effect, e.g. PTS, is predicted to occur for a particular scenario, or *effect areas* – the corresponding area affected. Both are useful, since effect ranges often inform whether mitigation procedures (such as an observational perimeter around an activity) are appropriate, while the effect area is more relevant for understanding the number of animals that are predicted to be affected, in combination with animal density estimates.

The relationship between the effect range or area predicted under one set of criteria versus the other, for any given scenario and functional hearing group, is a function of the criteria threshold values and weightings, as well as the propagation losses across the scenario domain (which depend on bathymetry and environmental parameters such as seabed composition).

Peak SPL Criteria

In the case of the peak SPL criteria, the analysis is simplified due to the absence of any weightings and the range relationship can be obtained by balancing the threshold difference against the peak SPL propagation loss. These differences were modelled for each of the scenarios in Table 10, using peak SPL propagation models derived from the literature (Soloway & Dahl 2014 for explosions; Galindo-Romero, Lippert & Gavrilov 2015 for seismic airguns; Lippert *et al.* 2015 for pile driving). Figure 7 shows the resulting range-range and area-area plots for low- and high-frequency cetaceans (the two functional hearing groups for which the peak SPL threshold differs). These plots show the range or area for which PTS would be expected under the NOAA criteria, based on a given range or area predicted using the Southall criteria, and vice versa. For example, Figure 7a indicates that if the Southall criteria predict a PTS range of 5 km for low-frequency cetaceans, using the same model this should correspond to a range of approximately 15 km under the NOAA criteria. The line of equivalence is shown as a dashed line: if the plots are above this line, it indicates that the NOAA criteria are more precautionary, and vice versa.

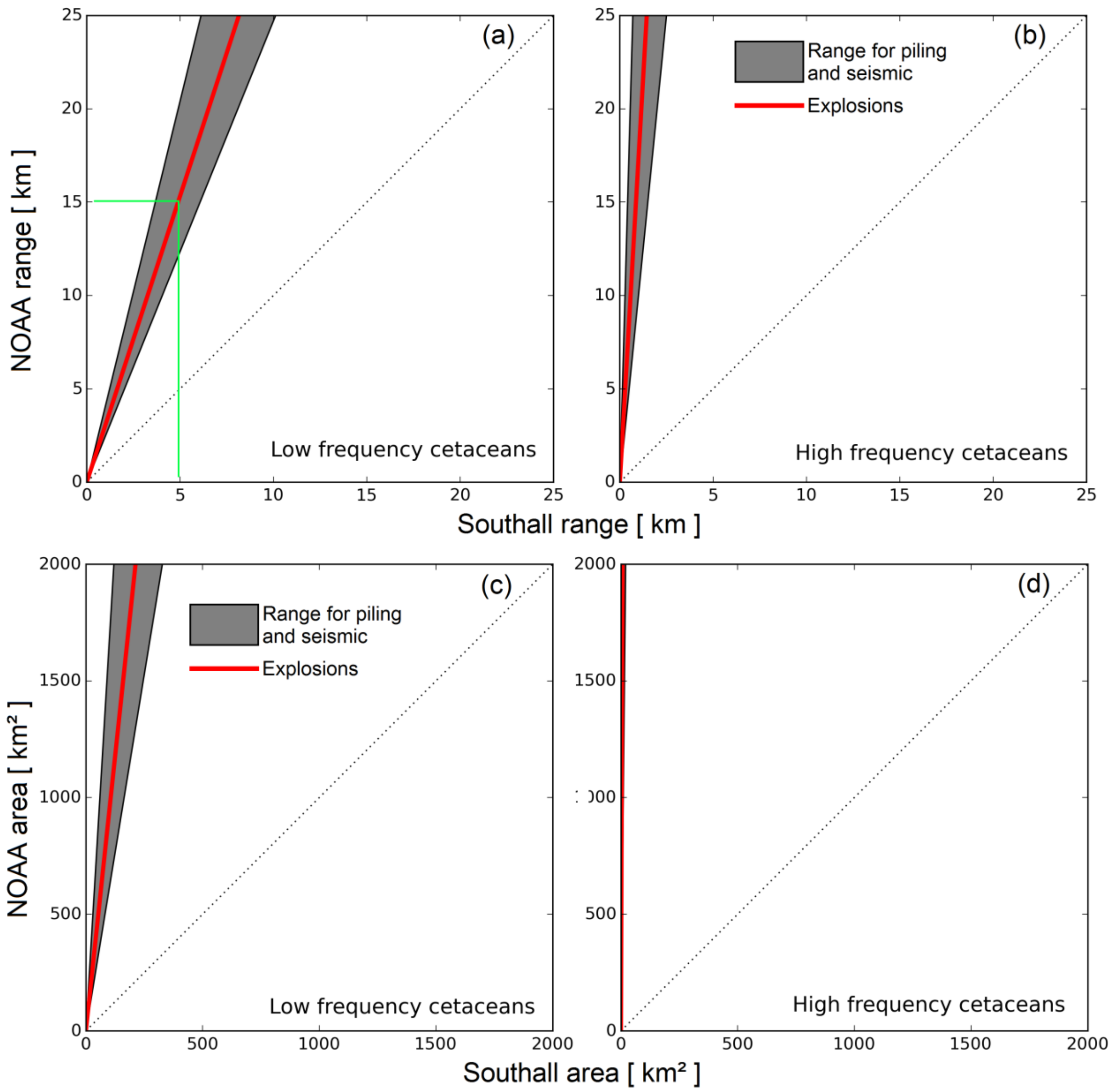

Figure 7: Range-range and area-area plots for peak SPL criteria, for functional hearing groups whose peak SPL PTS threshold differs between the criteria. Green line in (a) illustrates that a 5 km PTS prediction for low-frequency cetaceans under the Southall criteria corresponded to a 15 km prediction under the NOAA criteria for these scenarios.

Cumulative SEL Criteria

It is important to highlight that predicted cumulative effect zones can be strongly influenced by the modelling assumptions, particularly whether animals are assumed to flee from the source at the onset of disturbance. (The modelling undertaken for this assessment has assumed a static receptor). Therefore, the impact ranges provided herein are solely presented to allow assessment of the relative differences between the Southall and NOAA criteria rather than typical ranges.

In the case of the cumulative SEL criteria, the analysis is complicated by the presence of the weightings which, in conjunction with the frequency-dependent propagation losses across the domain, can result in adjusted threshold differences that are variable with range, as illustrated in Figure 6. Thus, the balancing of these differences against the propagation losses for solving the ranges relationship is in general not feasible analytically, but it can be accomplished numerically.

Accordingly, we have produced ‘range-range’ plots (Figure 8) and ‘area-area’ plots (Figure 9), which show the relationship between the effect ranges or areas predicted under one set of criteria versus the other, according to the modelling scenarios which were undertaken. These plots would be useful, for example, if an assessment had been undertaken using the Southall criteria, but a subsequent assessment of the same activity used the more recent NOAA criteria. In this case, Figure 8 and Figure 9 could provide guidance on the expected differences in ranges and areas predicted.

For example, it can be seen from Figure 8(a) and Figure 9(a) that any range/area predicted for low-frequency cetaceans under the Southall criteria would be larger for the same parameters under the NOAA criteria. The opposite is true for mid-frequency cetaceans and phocids, with the exception of the vibratory piling example within 19.6 km of the source (although note that it is highly improbable that vibratory piling would ever lead to PTS at such ranges). For high-frequency cetaceans, the results for the seismic airgun scenarios are more complicated, since they indicate greater precaution under the Southall criteria at ranges greater than 3.2 km (for the NEA Scenario 8) or 3.8 km (for the NNS Scenario 7) (Figure 6c) although these are well outside the PTS onset effect range. The PTS effect ranges under each set of criteria for all the modelled scenarios specified in Table 10, predicted using the peak SPL and the cumulative SEL metrics, are shown in Table 11 and Table 12, respectively.

We note several points to aid in the interpretation of Figures 8 and 9:

1. The degree of curvature on the line is indicative of the extent to which the auditory weighting affects the criteria differences and, to a lesser extent, reflects the changes in the sound propagation regime from the near to far field. The degree of curvature is reduced when the variation with range of the criteria differences (shown in Figure 6) is small. It should be noted that in the case of peak SPL results shown in Figure 7, all the lines were straight as no frequency weighting is applied for this criterion.

2. Although PTS is the focus of this report, since the differences between the Southall and NOAA thresholds for TTS and PTS are both 15 dB, the results presented here also hold for TTS.

A general trend appears to be that NOAA becomes less precautionary relative to Southall as the water depth increases.

We note several further points to highlight from the results in Tables 11 and 12:

1. For peak SPL, the largest difference observed was for high-frequency cetaceans and UXOs, with Southall predicting 580 m and the NOAA criteria 10,050 m (i.e. the NOAA criteria being more precautionary/conservative).
2. For cumulative SEL, the NOAA criteria were substantially more precautionary for low-frequency and high-frequency cetaceans, and vice versa for mid-frequency cetaceans and phocid seals.

Table 11

PTS effect ranges predicted using the peak SPL metric under each set of criteria for the modelled scenarios specified in Table 7. Bold values indicate non-trivial PTS effect ranges (e.g. 50 m or greater). N/A denotes no PTS effect ranges.

	Low-Frequency Cetaceans		**Mid-Frequency Cetaceans**		**High-Frequency Cetaceans**		**Phocid**	
Scenario	Southall	NOAA	Southall	NOAA	Southall	NOAA	Southall	NOAA
1. Pile driving OWF NNS	<50 m	<50 m	<50 m	<50 m	<50 m	**150 m**	<50 m	<50 m
2. Pile driving OWF SNS	<50 m	<50 m	<50 m	<50 m	<50 m	**240 m**	<50 m	<50 m
3. Pile driving inshore	<50 m	<50 m	<50 m	<50 m	<50 m	**53 m**	<50 m	<50 m
4. Vibropiling	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
5. UXO detonation NNS	**580 m**	**1780 m**	**580 m**	**580 m**	**580 m**	**10050 m**	**1970 m**	**1970 m**
6. UXO detonation SNS	**580 m**	**1780 m**	**580 m**	**580 m**	**580 m**	**10050 m**	**1970 m**	**1970 m**
7. Seismic NNS	<50 m	<50 m	<50 m	<50 m	<50 m	**50 m**	<50 m	<50 m
8. Seismic NEA	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m	<50 m

Table 12

PTS effect ranges predicted using the cumulative SEL metric under each set of criteria for the modelled scenarios specified in Table 7. Bold values indicate non-trivial PTS effect ranges (e.g. 50 m or greater).

	Low-Frequency Cetaceans		**Mid-Frequency Cetaceans**		**High-Frequency Cetaceans**		**Phocid**	
Scenario	Southall	NOAA	Southall	NOAA	Southall	NOAA	Southall	NOAA
1. Pile driving OWF NNS	**2808 m**	**14081 m**	**1525 m**	**50 m**	**1233 m**	**5199 m**	**11453 m**	**2206 m**
2. Pile driving OWF SNS	**2602 m**	**11522 m**	**1658 m**	**141 m**	**1356 m**	**5882 m**	**9210 m**	**2473 m**
3. Pile driving inshore	**581 m**	**2627 m**	**422 m**	<50 m	**359 m**	**2515 m**	**1993 m**	**726 m**
4. Vibropiling	<50 m	**299 m**	<50 m	<50 m	<50 m	**1451 m**	**141 m**	**100 m**
5. UXO detonation NNS	**446 m**	**1575 m**	**50 m**	<50 m	**50 m**	**2369 m**	**1261 m**	**141 m**
6. UXO detonation SNS	**399 m**	**1644 m**	**100 m**	<50 m	**50 m**	**2769 m**	**1300 m**	**315 m**
7. Seismic NNS	**2015 m**	**3960 m**	**100 m**	<50 m	**50 m**	**100 m**	**3546 m**	**100 m**
8. Seismic NEA	**3232 m**	**4736 m**	**100 m**	<50 m	**50 m**	**100 m**	**3994 m**	**100 m**

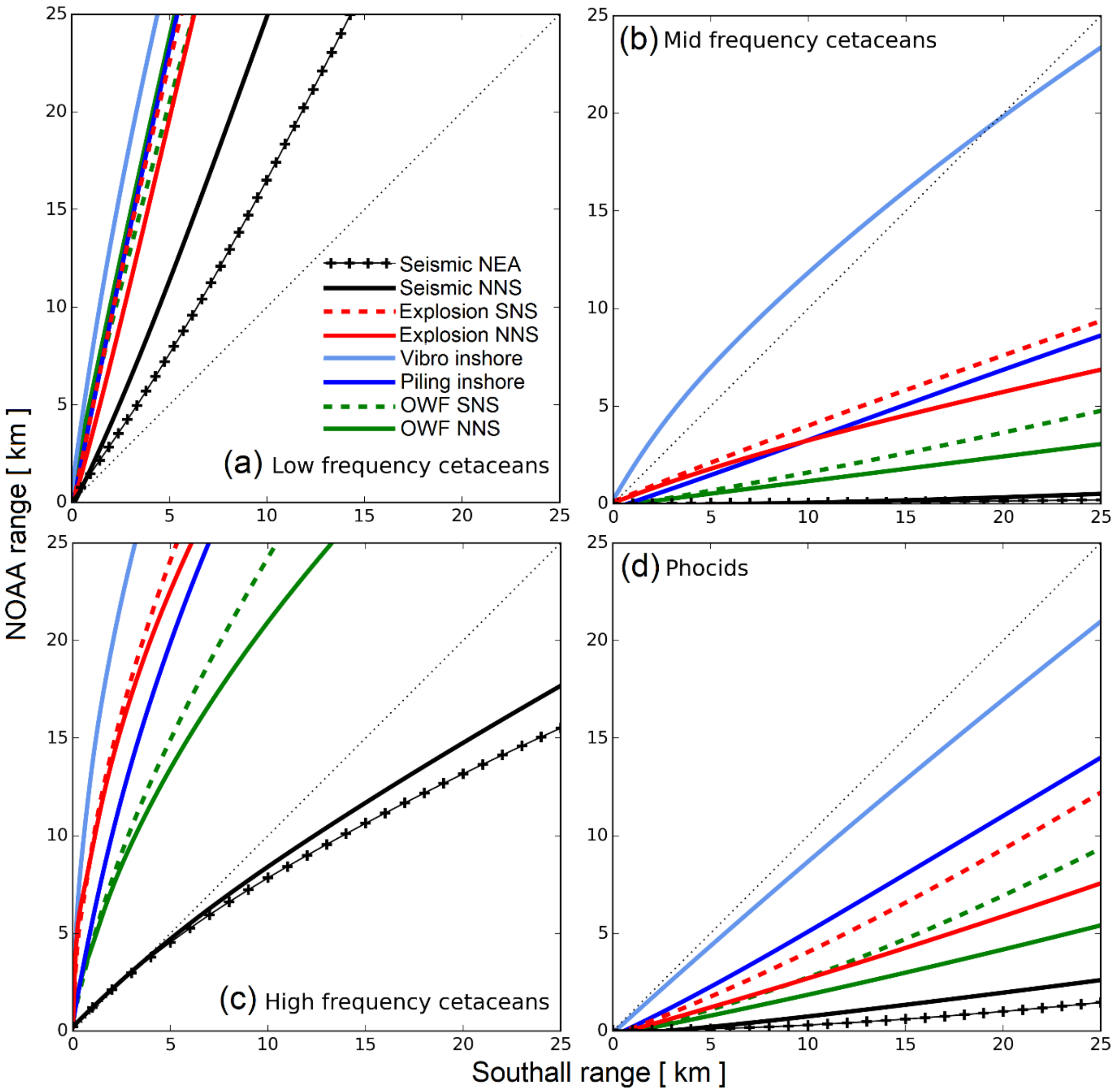

Figure 8: Relationship between the effect ranges predicted under each set of criteria, based on modelling scenarios described in the text. NEA = Northeast Atlantic; NNS = Northern North Sea; SNS = Southern North Sea; OWF = offshore wind farm.

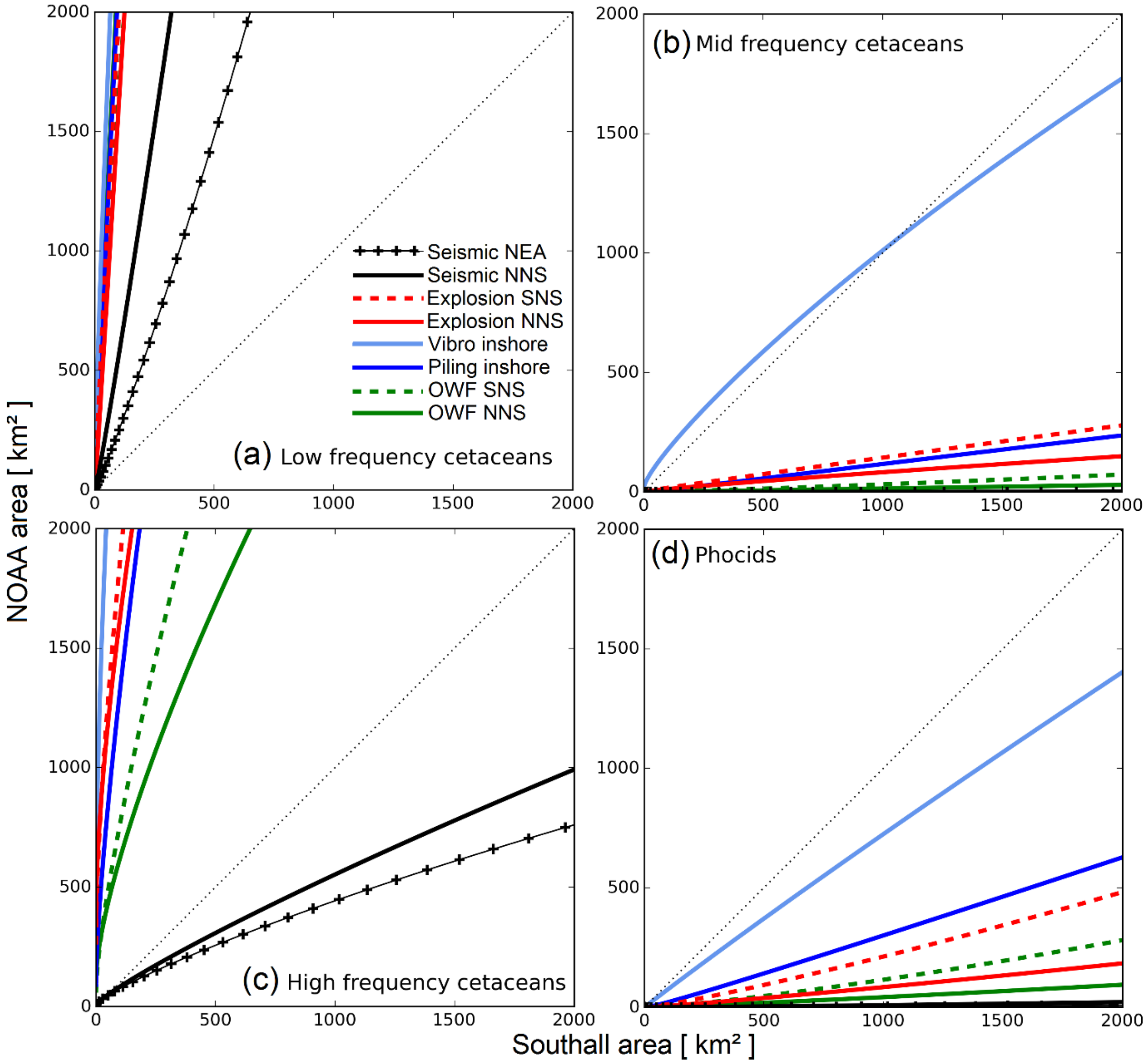

Figure 9: Relationship between the effect areas predicted under each set of criteria, based on modelling scenarios described in the text. NEA = Northeast Atlantic; NNS = Northern North Sea; SNS = Southern North Sea; OWF = offshore wind farm.

Conclusions

The results clearly illustrate the overall differences between the Southall criteria and the NOAA criteria in terms of their overall levels of precaution for each functional hearing group. The indications of greater or lesser precaution shown in Table 9 should hold generally for these types of sound source, although the absolute decibel differences will vary according to the frequency composition of the sound spectrum.

As the analysis of the effects of propagation demonstrated, the absolute differences between the cumulative SEL criteria will vary with distance from the source due to the frequency-dependent effects of sound propagation. These propagation effects will not typically affect which set of criteria are more or less precautionary. The range-range and area-area plots, shown in Figure 8 and Figure 9, can assist regulators by providing guidance on the likely change in effect range or area resulting from a reassessment using the other set of criteria (most likely a reassessment using the more recent NOAA criteria to update an assessment using the Southall criteria).

Caution should be exercised to avoid applying these results too widely or with unwarranted precision: the absolute decibel differences reported for the criteria should be broadly similar for other similar environments and sources, but variability should be expected according to the specifics of any particular modelling scenario assessed.

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