International regulations on the impact of pile driving noise on marine mammals – A literature review

Klaus Lucke[1] and Marije Siemensma[2]

Report number C044.13



IMARES Wageningen UR

(IMARES - Institute for Marine Resources & Ecosystem Studies)

Client: Rijkswaterstaat Noordzee
Martine Graafland
De Hague, The Netherlands

Publication date: 13th March 2013

IMARES WAGENINGEN UR

IMARES is:

- an independent, objective and authoritative institute that provides knowledge necessary for an integrated sustainable protection, exploitation and spatial use of the sea and coastal zones;
- an institute that provides knowledge necessary for an integrated sustainable protection, exploitation and spatial use of the sea and coastal zones;
- a key, proactive player in national and international marine networks (including ICES and EFARO).

[1] IMARES Wageningen UR, Postbus 167, 1790 AD Den Burg, The Netherlands
[2] Marine Science and Communication (MS&C), Bosstraat 123, 3971 XC Driebergen-Rijssenburg, The Netherlands

P.O. Box 68
1970 AB IJmuiden
Phone: +31 (0)317 48 09 00
Fax: +31 (0)317 48 73 26
E-Mail: imares@wur.nl
www.imares.wur.nl

P.O. Box 77
4400 AB Yerseke
Phone: +31 (0)317 48 09 00
Fax: +31 (0)317 48 73 59
E-Mail: imares@wur.nl
www.imares.wur.nl

P.O. Box 57
1780 AB Den Helder
Phone: +31 (0)317 48 09 00
Fax: +31 (0)223 63 06 87
E-Mail: imares@wur.nl
www.imares.wur.nl

P.O. Box 167
1790 AD Den Burg Texel
Phone: +31 (0)317 48 09 00
Fax: +31 (0)317 48 73 62
E-Mail: imares@wur.nl
www.imares.wur.nl

IMARES, institute of Stichting DLO is registered in the Dutch trade record nr. 09098104,
BTW nr. NL 806511618

A_4_3_2-V13

Contents

1. Summary

Many marine mammal species rely on their acoustic sense for communication, social interaction, navigation, and foraging. Odontocetes (toothed whales, such as the harbour porpoise) in particular use echolocation for navigation and foraging.

At the same time, underwater sound levels emitted during offshore pile driving are very high, with received peak-to-peak sound pressure levels (SPLs) exceeding 200 dB re 1 µPa at 100 m and sound exposure levels (SELs) of single pulses exceeding 180 dB re 1 µPa^{2}s in 100 m from the foundation (ICES 2010). Such high levels have the potential to inflict temporary or permanent damage to the auditory system of marine mammals (Nachtigall *et al.* 2003, Finneran *et al.* 2005, Kastak *et al.* 2005, Lucke *et al.* 2009, Popov *et al.* 2011, Kastelein *et al.* 2012).

There is a variety of measures and approaches discussed and tested to mitigate the adverse effects linked to the installation of offshore wind turbines. Besides setting regulatory limits to the sound levels (noise exposure criteria) in general mitigation measures can subdivided into three categories: measures at the source, measures that affect the propagation and measures at the receiver side (Ainslie *et al.* 2009). This review gives a comprehensive overview of these mitigation measures, which range in their developmental stage from advanced prototypes to fully tested and commercially available systems.

The aim of implementing noise exposure criteria into offshore marine regulations is to prevent negative effects to marine fauna from exposure to intense anthropogenic sounds. This regulatory mitigation tool implies that all species at risk should be equally protected from auditory damage if these criteria are to be enforced. The biggest deficit, however, is the current lack of data on auditory sensitivity and tolerance to intense sound in many marine species. Most data on adverse auditory effects have been measured in only a small number of marine mammal species, and the data indicate substantial differences with regard to hearing sensitivity and vulnerability to adverse auditory effects between functional groups (species using high-frequency echolocation signals such as the harbour porpoise *vs.* species emitting mid-frequency signals like bottlenose dolphins e.g.). Consequently, any noise exposure criterion may be effective only if it is based on data from the 'most sensitive' species occurring in the area of concern. However, there are no internationally adopted exposure criteria for marine mammals yet and thus no consensus on which exposure levels are considered safe.

The regulation of offshore pile driving varies strongly between different countries throughout Europe as well as world-wide, first of all due to different legal requirements. Moreover, there are different approaches to defining the source level from offshore pile driving. Despite the complexity of measuring the sound emissions of pile driving and the on-going efforts to harmonise the technical standards, several countries have, or are in the process of developing guidelines for mitigation measures as an attempt to reduce the adverse effects of pile-driving and other impulsive sounds on marine life.

These guidelines for offshore pile driving are developed although substantial gaps in knowledge need to be filled to deal with the impact of anthropogenic sound emitted into the marine environment. Noise exposure criteria are defined and implemented into the regulatory framework only in the U.S.A. and Germany (with differences in their principal approach). A relatively small number of other countries has already set at least a regulatory framework including requirements for measurement of the emitted underwater sound, mitigation measures to reduce the emitted sound and monitoring as well as the assessment of the behavioural effects of this sound on marine animals. The general problem of effects of sound on the marine environment, however, has been recognised by numerous countries and international organisations. As scientific insight into the cause-effect relationship between sound and effects on marine mammals progresses (both in a quantitative and qualitative way), the regulatory frameworks evolve subsequently and in most countries the continuous advancement has been included into their regulations as an inherent factor. It is nevertheless evident that regulators when defining criteria.

2. Introduction

The aim of the "Vervolg Uitvoering Masterplan Wind" (VUM) is to generate the scientific and jurisdictional base for a Dutch exposure criterion for underwater sound emissions related to offshore wind turbines. This scientific research will focus on marine mammals as they are most prone to experience significant negative effects from exposure to intense sound. The target species for the VUM studies will be the harbour porpoise (*Phocoena phocoena*).

Sound levels emitted during pile driving are very high, with received peak-to-peak SPLs exceeding 200 dB re 1 µPa at 100 m and SELs of single pulses exceeding 180 dB re 1 $µPa^2s$ in 100 m from the foundation (ICES 2010). Such high levels have the potential to inflict temporary or permanent damage to the auditory system of marine mammals (Nachtigall *et al.* 2003, Finneran *et al.* 2005, Kastak *et al.* 2005, Lucke *et al.* 2009, Popov *et al.* 2011). There are no commonly adopted exposure criteria for marine mammals and thus no consensus on which exposure levels are considered safe or acceptable

A logical first step in developing a noise exposure criterion for the Netherlands is to collate all existing knowledge and information how this has been implemented in regulations elsewhere. In this literature study we review all available information on regulations concerning offshore pile driving; where appropriate this information is supplemented by regulations concerning other impulsive sound sources, such as seismic airgun signals and underwater explosions. Literature on country specific regulations is reviewed as well as information on regulations developed by/ for international bodies such as treaties for the protection of certain habitats or taxa. The literature database of IMARES and MS&C has been used as well as a comprehensive internet based search including Web of Science, Scopus, Google Scholar etc.; in addition national regulators have been contacted to gather detailed inside information. Case studies on the most relevant regulations are presented in more detail.

In addition, mitigation measures requested by national regulations are also reviewed. A list including a brief description of existing mitigation techniques and a synopsis of their efficiency is given.

A discussion of the most important aspects of the existing regulations, dissimilarities between national regulations, and their applicability to the Dutch situation concludes this study.

3. Effects of Underwater Sound on Marine Life

Several marine animal species rely on their acoustic sense for communication, social interaction, navigation, and foraging. Odontocetes (toothed whales, such as the harbour porpoise) in particular use echolocation for navigation and foraging.

The effects of sound on marine animals and the ranges over which they occur depend on the acoustic characteristics of the sound (level, spectrum, duration, rise time, duty cycle, *etc.*), the sound propagation environment, and the acoustic sensitivity of the animal under consideration. Figure 1 shows the relative extents of some of the possible zones of influence: audibility, behavioural response, masking, hearing threshold shift (TS) and physical injury.

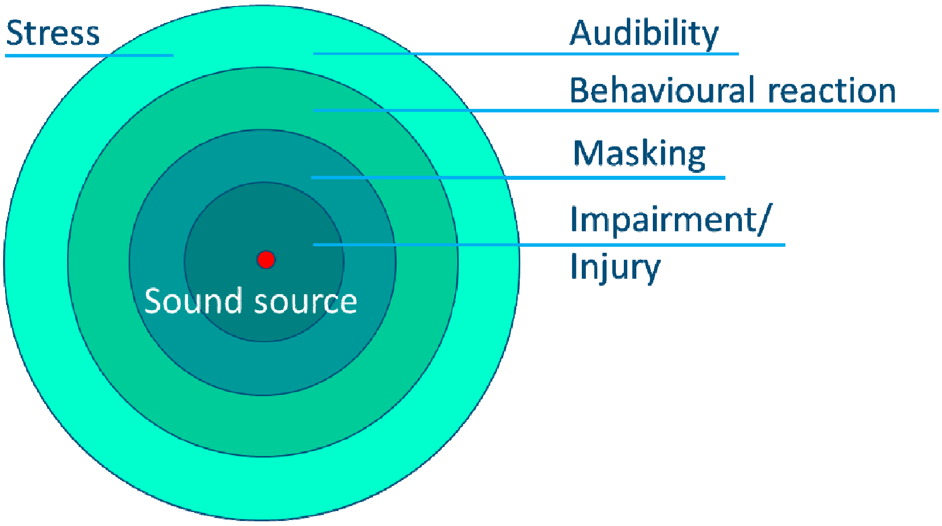

Figure 1: Schematic of zones of impact on a receiving marine mammal around a sound source (after Richardson et al. 1995) (Note: there is no clear zoning between effects and different effects can even overlap).

Any sound has the potential to acoustically mask the perception of another sound by a listener if the temporal and spectral characteristics of the signal of interest and the masking sound overlap sufficiently. This acoustic masking can have significant effects for a receiver (here: a marine mammal) if the masked signal is of biological importance. Underwater sound is one of the most important triggers for behavioural reactions in marine mammals.

The reaction can range from changes in swim direction and speed, dive duration, surfacing duration and interval, respiration rate, movement towards or away from the sound noise, and changes in acoustic behaviour. The reactions are individually variable and context specific, i.e. they depend on several factors including ambient noise, prior exposure (habituation *vs.* sensitisation), current behavioural state, age, gender, and health. While behavioural effects are now being considered in the context of noise exposure criteria (see PCAD, chapter 8), masking itself is not considered as a relevant parameter. However, the masking effect due to ambient noise in the North Sea needs to be taken into account with regard to audibility as well as the behavioural reactions.

Nevertheless, there is insufficient knowledge on behavioural and masking effects due to underwater noise in marine mammals. This makes these two categories almost intangible for regulatory purposes.

A potential consequence of exposure to intense sound is a loss of hearing sensitivity which is reflected in an elevated hearing threshold (i.e. a hearing threshold shift). This effect is called a Temporary Threshold Shift (TTS) if the hearing sensitivity returns to its normal level, or a Permanent Threshold Shift (PTS) if some residual amount of shift remains.

In addition, cumulative effects from temporal or spatial overlap in exposure to sound as well as other stressors have to be taken into account as they can interact in a constructive or destructive way, i.e. elevate the effect above a certain threshold if cumulative while the single stressor would not have a comparable effect. Different types of sound induced effects may be linked. For example, a TTS will affect the audibility of signals (e.g., of conspecific calls) and thus may alter or prevent the 'normal' behavioural response to the signals. While it is feasible to model cumulative sound exposure (Erbe and King 2009), the effects of cumulative sound exposure and the manner in which repeated exposure gets accumulated by the animal are unknown.

The consequences of any type of hearing impairment depend on the functional role sound plays in the life of the animal. Sound is used actively and passively by marine organisms to communicate (including courtship and territorial behaviour), to orient themselves in their three-dimensional environment, to avoid predators, and to detect and locate food. TTS can affect parts of the frequency range of an animals' functional hearing range or the entire hearing range, depending on the severity of the hearing impairment. In case of PTS most likely TTS, as the milder form of noise induced hearing loss, will be present over the entire frequency range of the animal's hearing. Consequently, the effects of TTS or PTS can range from a reduced capability to perceive biological meaningful signals from their environment (*i.e.*, from conspecifics, prey, or predators) to a reduced or, in extreme cases, totally disrupted foraging capability. Depending on the extent of the auditory impairment and the importance of sound perception for the exposed animal, changes in TTS and PTS can range from having no significant effect to being fatal.

Based on their approximate ranges of hearing frequency of the mammals involved marine mammal species were assigned to one of five functional hearing groups by Southall *et al.* (2007): low-, mid-, and high-frequency cetaceans, as well as pinnipeds (generalised: seals) listening in water and in air. The harbour porpoise is considered a high-frequency cetacean.

History of TTS research in cetaceans

Significant research into marine mammal TTS occurred after the 1994 report by the US National Research Council (National Research Council 1994) identified the need to investigate whether marine mammals experience greatest TTS at a frequency 1/2-octave above the frequency of exposure when exposed to loud tones, as has been shown in terrestrial mammals. Nachtigall *et al.* (2004) observed an average threshold shift of 5 dB at 8 kHz and an 8 dB shift at 16 kHz in a bottlenose dolphin following exposure to octave-band noise (OBN) centred at 7.5 kHz. A similar upward frequency shift also has been observed by Schlundt *et al.* (2000) and Finneran *et al.* (2007) for mid-frequency cetaceans. These findings provide "strong evidence for fundamental similarities in cochlear micromechanics in marine and land mammals" (National Research Council 1994, p51) and further justify the judicious extrapolation of TTS data within marine mammal functional hearing groups and from terrestrial to marine mammals.

Schlundt *et al.* (2000) reported TTS in five bottlenose dolphins and two belugas exposed to 1-s pure tones. This paper also included a re-analysis of TTS data from a technical report by Ridgway *et al.* (1997). At frequencies of 3 kHz, 10 kHz, and 20 kHz, SPLs necessary to induce TTS onset were 192–201 dB re 1 μPa (192–201 dB re 1 μPa^2s SEL). The mean exposure SPL for TTS onset was 195 dB re 1 μPa (195 dB re 1 μPa^2s SEL). In this context, the different metrics for the tonal sources used in this study and those involving pulses are appropriate. The SPL and SEL values are identical in this special case, however, because of the 1-s duration stimuli. At 0.4 kHz, no subjects exhibited shifts after SPL exposures of 193 dB re 1 μPa (193 dB re 1 μPa^2s SEL). Data at 75 kHz were inconsistent where one dolphin exhibited a TTS after exposure to 182 dB re 1 μPa (182 dB re 1 $\mu Pa^2 \cdot$s SEL) but not at higher exposure levels, while the second dolphin experienced no threshold shift after exposure to a maximum level of 193 dB re 1 μPa (193 dB re 1 μPa^2s SEL). The shifts in hearing sensitivity occurred most often at

0.5 to 1 octave above the frequency of the fatiguing stimulus (*i.e.*, the intense acoustic stimulus used to elicit the TTS).

Nachtigall *et al.* (2003) found an average TTS_{20} (20 min after sound cessation) in a bottlenose dolphin of 11 dB following a 30 min net exposure to OBN with a 7.5 kHz centre frequency (179 dB re 1 μPa, 212–214 dB re 1 $μPa^2$·s SEL), the net exposure time being the total experiment time minus the time required for the subject to surface and breathe. Exposure during breathing periods was measured and included in the SEL value. No TTS_{20} was observed after exposure to the same OBN at lower maximum SPL values of 165 and 171 dB re 1 μPa (198–200 and 204–206 dB re 1 $μPa^2$s SEL, respectively).

Using AEP methods, Nachtigall *et al.* (2004) found TTS_5 of to 8 dB following nearly 50-min exposures to OBN with a centre frequency of 7.5 kHz (160 dB re 1 μPa 0-peak, 193–195 dB re 1 $μPa^2$s SEL). The difference in results between the two Nachtigall *et al.* studies (2003, 2004; slightly lower TTS after exposure to much lower exposure energy) was attributed to measuring TTS at a shorter interval after the exposure ended (5 *vs.* 20 min), and thus allowing less time for hearing recovery. Further, Nachtigall *et al.* (2004) measured hearing repeatedly until recovery. TTS recovery occurred within minutes or tens of minutes, depending on the amount of threshold shift. Generally, the recovery rate was 1.5 dB of recovery per doubling of time and was consistent between studies (Nachtigall *et al.* 2003, Nachtigall *et al.* 2004).

Finneran *et al.* (2005) measured TTS in bottlenose dolphins exposed to 3 kHz tones with durations of 1, 2, 4, and 8 s and at various SPL values. Tests were conducted in a quiet pool in contrast to previous studies in San Diego Bay where thresholds were masked by broadband sound. Small amounts of TTS (3–6 dB) occurred in one dolphin following exposures of 190–204 dB re 1 $μPa^2$s SEL. These results are consistent with those of Schlundt *et al.* (2000), indicating that their results were not significantly affected by the use of masked hearing thresholds in quantifying TTS. In general, the SEL necessary for TTS onset was consistent across the range of exposure durations, whereas SPLs causing TTS onset tended to decrease with increasing exposure duration. These results confirmed that, for these testing conditions (bottlenose dolphins exposed to 8-s tones of variable SPL), TTS magnitude was best correlated with exposure SEL rather than SPL.

Schlundt *et al.* (Schlundt *et al.* 2006) reported on the growth and recovery of TTS in a bottlenose dolphin exposed to 3 kHz tones at SPLs up to 200 dB re 1 μPa with durations up to 128 s. The highest SEL was 217 dB re 1 $μPa^2$·s, which caused a TTS_4 of ~23 dB. All thresholds recovered to baseline values within 24 h, most within 30 min. The growth of TTS_4 with increasing SEL was ~1 dB TTS per dB of SEL for TTS_4 of 15 to 18 dB.

Finneran *et al.* (2007) measured TTS in a bottlenose dolphin after single and multiple exposures to 20 kHz tones. Hearing thresholds were estimated at multiple frequencies (10–70 kHz) both behaviourally and electrophysiologically (by measurement of multiple auditory steady-state responses (ASSR)). Three experiments were performed: two featured single exposures of 20 kHz tones, 64 s long at 185–186 dB re 1 μPa; and one featured three 20 kHz, 16-s exposures separated by 11 and 12 min, with a mean SPL of 193 dB re 1 μPa (±0.8 dB). Hearing loss was frequency dependent, with the largest TTS occurring at 30 kHz, less at 40 and 20 kHz, and little or no TTS at other measured frequencies. AEP threshold shifts reached 40–45 dB and were larger than behavioural shifts, which were 19–33 dB. Complete recovery required up to 5 days, with the recovery rate at 20 kHz being approximately 2 dB/doubling of time (under Marine Mammal Noise Exposure Criteria 439) and the rate at 30 kHz and 40 kHz was about 5–6 dB/doubling of time.

Finneran *et al.* (2010) measured TTS in a bottlenose dolphin after exposure to a sequence of four 3-kHz tones with durations of 16 s and SPLs of 192 dB re 1 μPa. The tones were separated by 224 s of silence, resulting in duty cycle of about 7%. The resulting growth and recovery of TTS were compared to experimentally measured TTS in the same subject exposed to single continuous tones with similar SPLs. The data confirm the potential for accumulation of TTS across multiple exposures and for recovery of hearing during the quiet intervals between exposures. The degree to which various models could predict the growth of TTS across multiple exposures was also examined.

Most marine mammal TTS data result from only small amounts of induced TTS. Finneran *et al.* (2010) present experimental data for the growth and recovery of larger amounts of TTS up to 23 dB in two bottlenose dolphins. Exposures consisted of 3 kHz tones with durations from 4 to 128 s and SPLs from 100 to 200 dB re 1 µPa. The resulting TTS data were combined with existing data from two additional dolphins to develop mathematical models for the growth and recovery of TTS. TTS growth was modelled as a function of exposure duration and SPL. TTS recovery was modelled as a double exponential function of TTS_4 and recovery time.

TTS research in Porpoises

More recently TTS research was expanded to high-frequency cetaceans. TTS data are published for harbour porpoises (*Phocoena phocoena*; Lucke *et al.* 2009 and Kastelein *et al.* 2012b) and Yangtze finless porpoises (*Neophocaena phocaenoides asiaeorientalis*; Popov *et al.* 2011). These species have similar auditory anatomy to the bottlenose dolphins and beluga, but have better high-frequency hearing, which corresponds to the higher energy peak in the frequency spectrum of their echolocation calls.

Lucke *et al.* (2009) conducted a TTS study on a harbour porpoise to provide information for the definition of noise exposure criteria for this species. The measurements of TTS were conducted on a captive animal by measuring AEPs in response to amplitude-modulated sounds. After obtaining baseline hearing data the animal was exposed to single airgun stimuli at increasing received levels. Immediately after each exposure the animal’s hearing threshold was tested for significant changes. The received levels of the airgun impulses were increased until TTS occurred. At 4 kHz, the predefined TTS criterion was exceeded at a received peak-to-peak SPL of 199.7 dB re 1 µPa (164.3 dB re 1 $\mu Pa^2 s$ SEL). The animal consistently showed avoidance behaviour to received peak-to-peak SPLs above 174 dB re 1 µPa (145 dB re 1 $\mu Pa^2 \cdot s$ SEL). These elevated levels of baseline hearing sensitivity indicate potentially masked acoustic thresholds[1]. Therefore, the resulting TTS levels should be considered masked TTS levels. These levels are lower than for any other cetacean species tested thus far.

In Yangtze finless porpoises, Popov et al. (2011) investigated effects of fatiguing sound on hearing thresholds at frequencies of 32, 45, 64, and 128 kHz. Their sound parameters were 0.5, -1, 0.5 octave bandwidth relative to the test frequency, at levels of 150 dB re 1 µPa (140–160 dB re 1 µPa in one measurement series), with 1–30 min exposure time. Thresholds were evaluated with AEP allowing the tracing of threshold variations with a temporal resolution better than 1 min. The most effective fatiguing sound was centred one half-octave below the test frequency. The TTS depended on the frequencies of the fatiguing sound and test signal: The lower the frequencies, the bigger the sound effect. The time-to-level trade of the sound effect was incomplete: the change of sound level by 20 dB resulted in a change of TTS level by nearly 20 dB, whereas a tenfold change in sound duration resulted in a TTS level increase of 3.8–5.8 dB. The results also showed that substantial threshold recovery was possible within a few minutes of sound exposure cessation.

Kastelein et al. (2012) investigated temporary threshold shifts (TTS) and recovery in a harbour porpoise after octave-band sound at 4 kHz. In this study a harbor porpoise was exposed to fatiguing sound at 18 sound pressure level (SPL) and duration combinations. Its temporary hearing threshold shift (TTS) and hearing recovery were quantified with a psychoacoustic technique. Octave-band white sound centred at 4 kHz was the fatiguing stimulus at three mean received SPLs (124, 136, and 148 dB re 1 µPa) and at six

[1] A masked acoustic threshold is the quietest level of the signal perceived when combined with a specific masking noise. If there is no masking noise the threshold is likely to be lower.

durations (7.5, 15, 30, 60, 120, and 240 min). The approximate received sound exposure levels (SELs) varied between 151 and 190 dB re 1 μPa2 s. Hearing thresholds were determined for a narrow-band frequency-swept sine wave (3.9–4.1 kHz; 1 s) before exposure to the fatiguing sound, and at 1–4, 4–8, 8–12, 48, and 96 min after exposure. The lowest sound exposure level (151 dB re 1 μPa2 s) which caused a significant TTS1–4 was due to exposure to a sound pressure level of 124 dB re 1 μPa for 7.5 min. The maximum TTS1–4, induced after a 240 min exposure to 148 dB re 1 μPa, was around 15 dB at a sound exposure level of 190 dB re 1 μPa2 s. The recovery time following TTS varied between 4 min and under 96 min, depending on the exposure level, duration, and the TTS induced.

Moreover, studies have shown that hearing loss after sound exposure is not necessarily correlated with the total energy of exposure. Exposure experiments with bottlenose dolphins (Finneran *et al.* 2009) revealed that the correlation between SEL and TTS is limited to impulses and that the equal energy hypothesis (i.e. the same amount of acoustic energy in different signals will cause comparable auditory effects) does not apply to long-duration exposures (>16 s). Finneran *et al.* (2011) confirmed the potential for accumulation of TTS in a bottlenose dolphin from multiple exposures to a sequence of four 3-kHz tones with durations of 16 or 64 s and SPLs of 192 dB re 1 μPa.

Furthermore, rapid amplitude change (‘kurtosis’) was identified as another factor influencing the amount of TTS elicited (Le Prell 2010).

The TTS data from Nachtigall *et al.* (2003, 2004) as well as Finneran *et al.* (2000, 2002, 2005, 2007, 2010, 2011) were achieved by testing bottlenose dolphins and beluga whales. These species are categorised by Southall *et al.* (2007) into the functional group of mid-frequency echolocators based on the spectrum of their echolocation signals. Harbour porpoises, in contrast, which were tested by Lucke *et al.* (2009) are high-frequency echolocators in comparison. Moreover, harbour porpoises are much smaller than the other species tested. Based on these results as well as controlled exposure experiments conducted by Ketten *et al.* (2006) it can be concluded that both the severity and number of impacts from blasts on fresh marine mammal specimen are mass-dependent and correlated with received peak pressure in dolphins and porpoises. If this mass-dependency applies not only to shock waves but also to impulsive sounds and extends also to larger cetaceans such as humpback whales it could possibly indicate that larger animals have a higher tolerance to impulsive sound than smaller ones. On the other hand, larger animals are supposed to have a much higher (*i.e.*, better) sensitivity to low frequency sounds as indicated by their low frequency sound emissions. This would indicate that larger cetaceans are much more prone to negative effects (both in terms of behavioural and physical effects) from the low frequency centred pile driving sound than dolphins or porpoises.

TTS Induced by Impulsive Sources

Finneran *et al.* (2000) exposed two bottlenose dolphins (*Tursiops truncatus*) and one beluga whale (*Delphinapterus leucas*) to single pulses from an explosion simulator generating frequencies above 1 kHz. No substantial (> 6 dB) threshold shifts were observed in animals exposed to a single pulse at the highest received exposure levels of 221 dB re 1 $\mu Pa_{peak\text{-}to\text{-}peak}$ (179 dB re 1 $\mu Pa^2 s$ SEL).

Finneran *et al.* (2002) exposed a beluga and a bottlenose dolphin to a seismic water gun that produced a single acoustic pulse (160 kPa (23 psi), 226 dB re 1 μPa peak-to-peak SPL, 186 dB re 1 $\mu Pa^2 s$ SEL). Measured TTS_2 (TTS measured 2 min after the exposure) for the beluga was 7 dB at 400 Hz and 6 dB at 30 kHz. Thresholds returned to within ± 2 dB of the pre-exposure value within 4 min of exposure. No TTS was observed in the bottlenose dolphin at the highest exposure condition (207 kPa (30 psi); 228 dB re 1 μPa peak-to-peak SPL, 188 dB re 1 $\mu Pa^2 s$ SEL). These studies demonstrated that, for very brief pulses, higher sound pressures were required to induce TTS than had been found for longer tones (see discussion below).

Permanent Threshold Shift (PTS)

Southall *et al.* (2007) suggested that noise exposure criteria for auditory injury should be based on exposures empirically shown to induce PTS onset. Since no such data existed for marine mammals at the time, they estimated PTS onset instead from TTS-onset measurements and from the rate of TTS growth with increasing exposure levels above the level eliciting TTS-onset. They presumed PTS to be likely if TTS is shifted by ≥ 40 dB.

Kastak *et al.* (2008) published the only data on PTS in a marine mammal. In their study, these methods were used with a harbour seal (*Phoca vitulina*) exposed to an underwater 4.1 kHz pure tone fatiguing stimulus. Sound levels and durations were gradually increased to a maximum received sound pressure of 184 dB re 1 μPa with a duration of 60 s SEL 202 dB re 1 $\mu Pa^{2}\cdot s$. Upon the second exposure to this stimulus, an initial threshold shift in excess of 50 dB was estimated at a test frequency of 5.8 kHz, a half-octave above the fatiguing tone. Recovery from this unexpectedly large shift occurred at a rate of -10 dB per log min, with an apparent PTS of 7 to 10 dB two months following exposure. A PTS threshold could not be deduced from these findings.

TTS studies of various odontocete species (and families) showed that differences in TTS can be greater than 20 dB (*e.g.*, Finneran *et al.* 2005, Lucke *et al.* 2009). Therefore, the data by Kastak *et al.* (2008) provide insufficient information to determine a PTS threshold for marine mammal species other than the harbour seal or even another marine mammal family (such as the dolphins).

Frequency Weighting

Based on the auditory data available for mid-frequency cetaceans and assumptions and models for low- and high-frequency cetaceans, Southall *et al.* (2007) derived various M-weighting functions. These functions are adapted from the weighting functions (such as A-weighting) used in human audiometry which are used to compensate for our relatively low hearing sensitivity at the high and low ends of the hearing range. To assess the potential effect of low and high frequencies, these functions adjust the received sound levels to account for the reduced perceived levels. Although Southall *et al.* (2007) used a very conservative approach and clearly stated that their approach had to be used with great reservations, the M-weighting was quickly adopted by several national regulators (*e.g.*, U.K.). The M-weighting functions are nearly flat between the lower and upper cut-off frequencies in the hearing curves of the particular functional hearing groups. For this reason, they are likely to over-estimate the effects of sound at very high and very low frequencies while underestimating the effects over the functional hearing range. New data by Finneran (2010) show that the shape of the M-weighting functions are indeed incorrect and need drastic corrections. Finneran and Jenkins (2012) proposed new weighting functions based on subjective loudness measurements in a bottlenose dolphin. From this equal loudness contours were derived, using the same procedures as those used to derive human equal loudness contours (e.g., Suzuki and Takeshima, 2004). This provided a set of auditory weighting functions based on equal loudness contours (“EQL weighting functions”) presented by Finneran and Schlundt (2011). Figure 2 compares the Finneran and Schlundt (2011) bottlenose dolphin EQL weighting functions with the Southall et al. (2007) M-weighting function for MF cetaceans (i.e. bottlenose dolphins).

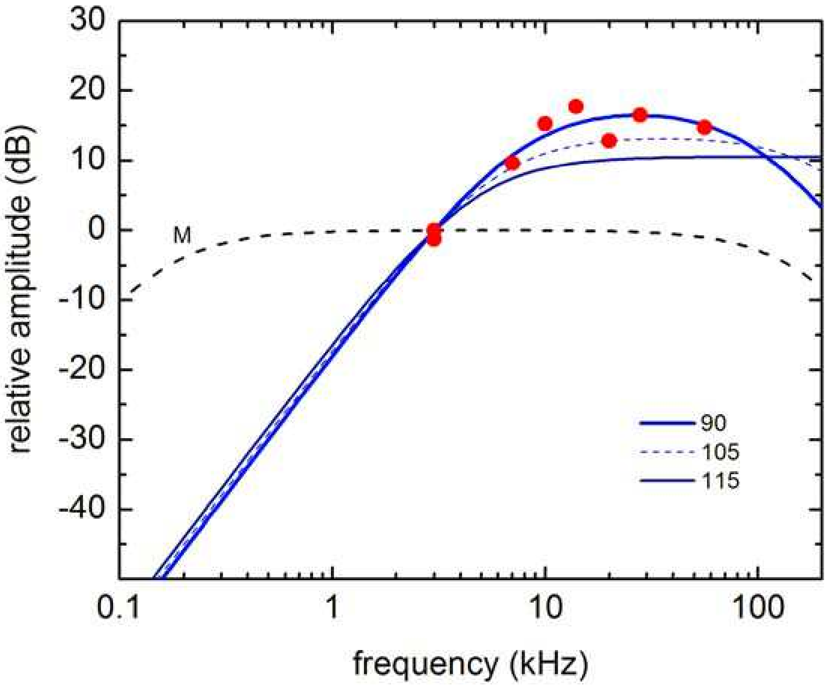

Figure 2: Comparison of dolphin auditory weighting function (solid lines), relative susceptibility to sound measured in a bottlenose dolphin (symbols), and Southall et al. mid-frequency cetacean "M-weighting" (dashed line). The functions were based on the equal loudness contours passing through 90, 105, and 115 dB re 1 µPa at 10 kHz (taken from Finneran and Jenkins 2012).

The relative susceptibility to sound shown in Figure 2 is based on the TTS onset data for bottlenose dolphins (Finneran, 2010; Finneran and Schlundt, 2009) which represents an exposure threshold. As pointed out by Finneran and Jenkins (2012) a sound exposure can also be described by the susceptibility of the listener, which represents the listener's sensitivity to sound. High values of susceptibility indicate frequencies where sound is more hazardous. The susceptibility data can be directly compared to auditory weighting functions, which preferentially emphasize (apply larger weight to) frequencies where sound is more hazardous and de-emphasize those frequencies where sound is less hazardous.

Moreover, the differences found in the TTS thresholds, *e.g.*, between dolphins and porpoises, indicate that differences tolerance to intense sound, and thus in the weighting functions, between the different functional groups of cetaceans are much larger than anticipated by Southall *et al.* (2007). Until more systematic data are available on in susceptibility in harbour porpoises (or other high-frequency cetaceans) these weighting functions for mid-frequency cetaceans should only be used with strong reservation to assess potential auditory effects on marine mammals.

Ambient Sound Consideration

The perception of any type of anthropogenic sound by marine mammals is governed by its auditory sensitivity, the received level of a specific sound but also by the actual acoustic scene the receiving animal is in. The most important aspect in this context is the background or ambient sound[2]. In the North Sea the level of background noise has increased over the past decades which can be linked to the

[2] *Background noise: total noise* without contributions of *self-noise*, usually composed of sound from many sources near and far; *ambient noise:* background noise remaining at a given position in a given situation when the specific sounds under consideration are suppressed (De Jong *et al.* 2011)

steady increase in the diversity and amount of marine anthropogenic activities. Numerous of these activities at sea are – either intentionally or as a mere by-product – linked to the emission of intense sound into the marine environment. Examples from other highly industrialised areas around the world indicate that this has led to a doubling of the underwater noise level per decade over the past 50+ years (Frisk 2007, Hildebrand, 2009). This increase has mainly been attributed to an increase in commercial shipping (Andrew *et al.*, 2002; Heitmeyer *et al.* 2004; Ross 2005, McDonald *et al.* 2006; Hatch *et al.* 2008). The most relevant contributors to anthropogenic ambient noise besides shipping are marine geophysical surveys conducted for hydrocarbon exploration, offshore construction (e.g. pile driving) and underwater explosions for ammunition removal (Richardson *et al.* 1995; OSPAR Commission 2000, Ainslie 2012). Any assessment of the potential impact of a specific sound such as pile driving impulses on the perception and behavioural reactions in marine mammals must take the background noise situation into account.

4. Mitigation

A variety of measures and approaches were developed to mitigate potential adverse effects linked to the construction of offshore wind turbines. On top of overarching regulatory noise exposure criteria Ainslie *et al.* (2009) distinguish mitigation measures into three categories: measures at the source, measures that affect the propagation and measures at the receiver side. Modifying the construction method is an example for a measure at the source. Installing a sound barrier such as a bubble curtain is a measure that affects the propagation. The use of acoustic deterrents can be seen as a measure at the receiver side. Useful compilations and assessments of the different types of foundation as well as mitigation techniques are provided though ICES (2009, 2010, 2011) and by the German Federal Agency for Nature Protection (Koschinski and Lüdemann 2011, in German). A list including a brief description of existing mitigation techniques and a synopsis of their efficiency is given below.

Sound mitigation at the source

There are several types of foundations for offshore wind turbines and different techniques to install them. The choice of most suitable foundation type and installation method is governed by several aspects, mainly water depth, weather conditions (maximum expected wave height), soil condition and from economic perspective, the costs. Every foundation has its own advantages and disadvantages. The standard types of piled foundations for offshore wind turbines include the mono-pile, a steel pile which is driven approximately several tens of meters into the seabed; the tripod foundation, which is based on technology used by the oil and gas industry. The piles on each corner of the structure are also driven several tens of meters into the seabed, depending on the soil conditions. This technology is generally used at deeper depths; A third method based on pile driving is the jacket foundation, suitable for water depths from 20-50 meters. Tripod or jacket structures are generally accepted as the more feasible foundation solutions in water depths in the 30-45 metres range, both having smaller piles than mono piles (OffshoreMarine 2010).

The most straight forward approach to reduce the sound emissions during the construction of wind turbines is to choose a different type of foundation, e.g. gravity foundations which don’t require pile driving or use of comparable techniques. Another approach is to reduce the sound emissions at the source by altering the pile driving technique or reduce the noise emissions by other adaptations.

Adaptation of pile-driving method

The most intense acoustic emissions in the context of constructing offshore wind turbines are linked to hydraulic or impulsive pile driving. This is currently the standard technique used to install offshore pile foundations. Most commonly a hydraulic hammer of up to several meters in diameter and several hundred to thousands kilojoules of impact energy is used to drive the piles into the sediment by repeatedly releasing a strong force onto the top of the pile. For offshore installations pile driving hammers can be used above water as well as submerged which results in differences in the sound emissions.

<u>Modification piling hammer</u>

Nehls *et al.* (2007) discuss potential options to reduce the piling sound for mono-pile foundations, such as modifying the hammer to reduce the strike. The physical principle of this approach is to prolong the impact time of the pile hammer, which results in a lower sound level. However, experiments didn’t show a feasible solution yet, and further experimental work is recommended. An advantage of modification of the piling hammer is that it tackles the problem of sound at the source, rather than damping it afterwards. Apart from a slight modification of the hammer settings, no change is required in the equipment and techniques used currently.

Modify piling interval

A study by SEAMARCO investigates the options using different inter-pulse intervals while driving mono piles, i.e. providing more time for the hearing system to recover in between piling (R. Kastelein, *pers. comm.*).

Alternative installation methods

Vibratory pile driving

The method of vibratory pile driving is based on rotating eccentric weights on top of the pile which create an alternating force on the pile, vibrating it into the ground (Ainslie *et al.* 2009). Vibratory pile driving is only suitable for smaller piles (Elmer 2010). The German BARD 1 offshore wind farm has been constructed using this alternative vibratory pile driving method. This offshore wind farm is fully exposed to the North Sea environment. BARD developed the patented 'Tripile' foundation system, which is suitable for water depths of 25 to around 40 metres and is, according to BARD, compacter, lighter and cheaper than other offshore foundation systems (www.bard.de).

Gravity based structures

Gravity based structures (GBS) consist of a large concrete or steel base, which rests on the seabed and is together with mono-piles the most used foundation. A GBS foundation is dependent on gravity to remain erect. Usually, no drilling or piling into the seabed is needed, however the seabed has to be prepared with in some cases dredging, gravel and concrete needed. Two examples of wind parks built with GBS foundations are the Belgian Thornton Bank Wind Farm 30 km off the coast of Belgium, starting in 2007 and the Danish wind farm Nysted, 10 km south of Nysted and 13 km west of Gedser, starting in 2002.

GBS foundations for larger turbines in deeper water depths is less feasible, as the practicality of concrete structures in deeper water depths is questionable. The size and weight of the foundation makes it increasingly difficult to handle (Saleem, 2011).

Drilling

Another foundation method is the use of concrete mono-piles which are drilled in the seabed based on horizontal tunnel-drilling methods. A reason to develop this concept is the fact that concrete mono-piles are less expensive compared to steel mono-piles; the method can be used for various soil types and underwater sound can be prevented or at least significantly reduced according to Ballast Nedam (www.bnoffshore.com). Weather conditions (expected maximum wave-heigths) might be a limiting factor for using this foundation method in the North Sea.

Floating installations

A new approach is the construction of offshore wind turbines on floating platforms. The main aim of this type of installation is to unlock areas with greater water depths for installations of OWTs. Several companies worldwide are currently developing various technical approaches following the same principle idea. While most efforts are still in the development phase or have achieved, only small-scale prototype testing a single full-scale turbine has been installed by StatoilHydro, within their project HYWIND in 2009 off the Norwegian coast. The underwater sound emissions of floating platforms depend mainly on the installation method for the mooring. If the anchors are e.g. piled into the sediment this technique does not provide a substantially different sound input into the marine environment as compared to conventional pile driving installations.

Suction bucket/ caisson

By creating a partial vacuum in the cylinder of the wind turbine fundament (through pumping the water out of the sealed cylinder) the resulting negative pressure within the chamber drives the fundament into the sediment. This process is supported by the hydrostatic pressure of the surrounding water mass. The depth limit of this approach is approximately 30 m.

A comparative analysis by Saleem (2011) concludes that alternatives for the steel mono-pile can provide some effective solutions in the short term, such as the jacket foundation with vibratory pile driving and gravity based structures. Other alternatives that can play a significant role in noise mitigation include the drilled concrete mono-pile, the screw-pile, floating foundations or the suction caisson method, using hydrostatic pressure and the weight of the structure to penetrate the soil. Although further development of alternative methods is needed, these can provide significant noise reduction.

Mitigation tools affecting sound propagation

There are several approaches and tools to mitigate the propagation of impulsive sound through the water. Most concepts are based on the impedance mismatch between air and water, i.e. benefitting from differences in physical properties in the two media.

Bubble curtain

A measure to mitigate sound propagation is by creating a sound barrier by releasing compressed air from a tube which is positioned either around a sound source or blocking off a specific underwater sound propagation path. Due to the strong impedance mismatch, the rising air bubbles reflect, scatter and absorb the sound leading to a reduced sound level on the opposite side of the barrier. The principle of using air bubble curtains to mitigate sound propagation has been known for several decades; as a noise mitigation method it had been successfully used before at near- and offshore constructions (e.g. Würsig *et al.* 2000) with sound attenuation ranging from 3 to 5 dB (Würsig *et al.* 2000) or even up to 20 dB (Spence *et al.* 2007). Although it leads to a reduction of noise, there are many difficulties such as the maximum depth, which makes it only feasible in shallow waters or the time and effort necessary for construction. Ainslie *et al.* (2009) note that the bubble screen itself is a source of sound, which may for some low frequencies (order hundreds of Hz) be louder than the sound source it is supposed to suppress.

However, most designs exist in a prototype stage only or have been especially designed for a specific type of construction. The boom in offshore wind energy and the resulting need for effective noise mitigation gave rise to revisit these techniques. Several companies and research institutions, mainly in Europe, developed existing designs further or newly created various types of air bubble curtains. With substantial research funding provided e.g. by the German government full scale air bubble curtains have been tested over the past years, all aiming at providing a state of the art method for the offshore industry to reduce the sound emissions from pile driving during the installation of offshore wind turbines.

A study by Lucke *et al.* (2011) conducted in Denmark, Kerteminde, provided the first direct sound measurements and behavioural observations of the efficacy of an air bubble curtain to mitigate the sound exposure of harbour porpoises. During construction work replacing a harbour wall in Denmark, 175 wooden piles were piled into the ground. At the same time three Harbour Porpoises were housed in a marine mammal facility on the opposite of the harbour showing strong avoidance reactions. To reduce the sound exposure an air bubble curtain was installed in a direct path between the piling site and the opening of the semi-natural porpoise pool. Pile driving impulses were simultaneously measured in front and behind the active air bubble curtain. Mean levels of sound attenuation were 14 dB for peak to peak values and 13 dB for sound exposure level values. As soon as the air bubble curtain was installed and operated, no further avoidance reactions of the animals to the piling activities were apparent showing the biological effectiveness.

Lucke *et al.* (2011) note that the effectiveness of such an air bubble system might be reduced in open waters due to stronger currents and greater water depths. Haemmerle *et al.* (2009) showed that uncontained bubble curtains in flowing water were not effective in attenuating pile driving sounds. Pile driving with contained bubble curtains (sleeve) were effective in attenuating pile driving sounds by 8-24 dB.

The attenuation effect of all methods is strongly frequency dependent and moreover can't eliminate the propagation of piling sound through the sediment (which can re-enter into the water column and contribute significantly to the received pile driving sound at greater distances). The sound mitigation techniques tested under offshore conditions or at least at a reasonable scale (Koschinski and Lüdemann 2011, Verfuβ 2012) comprise:

1.) Large scale air bubble curtain; this system was laid out as a ring with a diameter of 140 m around a pile driving site at a water depth of 26-33 m in the open North Sea. The achieved sound reduction ranged between 5.1 – 12.8 dB (SEL) and 6.8 – 14.2 dB (SPL/ Lpeak) at third-octave bands.
2.) Little bubble curtain, LBC (ISD 2010); this design comprises a stacked air bubble curtain deployed during the construction of offshore wind turbines at a water depth of approximately 40 m. The resulting sound reduction reached up to 15.5 dB (SEL).
3.) Confined bubble curtain (Caltrans 2001; Gunderboom 2011); air bubbles are confined over the entire water column between two sheets of fabric surrounding the foundation pile. This technique requires a large supporting structure and is limited in its use with regard to the current speed. The sound attenuation with this system reached 5 – 10 dB (rms and peak), better values were achieved with guiding the air bubbles within an isolating steel casing.
4.) Bubble stick (MENCK GmbH); compressed air is released from a perforated tube which is placed vertically in the water column. The bubble stick is positioned upstream from the foundation pile thus ensuring that the emerging bubbles surround most parts of the pile during the pile driving process.
5.) Noise mitigation screen (IHC Hydrohammer B.V.); in this approach a hollow, air-filled steel tube is placed around the outside of the foundation pile during the pile driving. The maximum damping efficiency was reached at frequencies between 500-1000 Hz. Preliminary data indicate a sound reduction of up to 25 dB (SEL) reached at third octave band frequencies between 1.2 and 2.5 kHz.
6.) Hydro Sound Damper (OffNoise-Solutions GmbH); this design is based on latex balloons and swim noodles arranged on a net surrounding the pile foundation over the entire water column. Studies on the Studies on the efficacy of using encapsulated air bubbles for sound reduction during pile driving have also been conducted by Lee *et al.* (2012).No data on the sound attenuation is available yet from a test under offshore conditions.
7.) BEKA Jacket (Bernhard Weyres Offshore); two half-shells of steel sheets filled with a polymer are fitted around the pile foundation during the pile driving. Additionally an air bubble curtain

is created on the inner and outer side of the shell. The maximum damping efficiency was reached at frequencies between 500-1000 Hz (no data on achieved attenuation levels available yet).

8.) Ring of fire hoses (MENCK GmbH); A single and double wall of vertically arranged fire hoses filled with compressed air are suspended around the pile foundation during pile driving. The maximum damping efficiency was reached at frequencies between 1.2 and 8 kHz with preliminary data indicating a maximum sound reduction of up to approximately 19 dB (SEL).

Solid barrier

Ainslie *et al.* (2009) refer to the use of solid physical barriers to reduce pile driving sound, filling a steel casing with foam instead of air. Attenuation up to 20 dB is reported. Another alternative is to remove water from a solid casing that surrounds the sound source (cofferdam). This expensive method effectively blocks the sound radiation into the water. This method is only feasible in shallow waters (Spence *et al.* 2007). In a report by Nehls *et al.* (2007) two methods, which offer sufficient prospect for a technical realization in practice have been identified: the inflatable sleeve and the telescopic tube, both bases on layers of air or foam around the pile. Sound levels in 500 m are attenuated by 15 or 20 dB respectively and the radius in which harmful or disturbing effects on marine mammals may be expected is reduced considerably. Nehls *et al*. (2007) recommend to further develop noise mitigation measures and to make them ready for practice.

Saleem (2011) provides an overview of modifications of mono-pile foundation or its installation technique for noise mitigation. Several new technologies, yet unproven on large scale, are described. Some are based on adapted piles, such as the use of screw piles or skirted mono-piles. The latter increases the lateral stability and therefore reduce the penetration depth of a mono-pile. The report distinguishes between engineering solutions that can be used for noise mitigation in the immediate short term without significantly changing to the current methods. This includes changing the parameter for pile stroke, using a vibratory hammer for pre-installing the mono-pile. Other solutions that can follow to further reduce sound in the short and medium-term include the isolation or damping of the sound and adapting the pile toe-shape.

Mitigation measures at the receiver

Acoustic deterrent devices

The concept of using an acoustic deterrent device (ADD) prior to a sound-producing activity is to deter marine mammals out of the area where the noise might have a negative effect on the animals. It is assumed that animals dislike the sound of an ADD enough to move away from the sound, to a distance, hopefully large enough for the noise to drop below impact levels. There are several acoustic deterrents available all producing (ultra)sound in the frequency range of 5 to 160 kHz. In theory ADDs have the potential to reduce the risk of causing injury to marine mammals, however in practice, not much is known about whether or not this assumption is correct. Marine mammals could theoretically even get attracted by the sounds the deterrent produces, i.e. approach the construction site out of curiosity. Studies quantifying the efficacy of ADDs to determine the applicability as suitable mitigation measure are needed (JNCC 2009). The use of acoustic deterrents adds to the total amount of underwater sound and the deterrent devices could reach levels which might have adverse effects on porpoises as well.

Kastelein *et al.* (2010) investigated the behavioural responses of a young harbour porpoise to three types of ADDs in a pool. While one device didn’t elicit avoidance responses in the porpoise, the other two – designed to deter seals – were found to be efficient as deterrence devices. They conclude that distance ranges, rather than exact distances, at which each device elicits a response should be considered due to high levels of variability in environmental variables.

Brandt *et al.* (2012) investigated the far-reaching effects of a seal scarer on harbour porpoises in the German North Sea using passive acoustic monitoring and to some extent simultaneous aerial surveying to specifically study the spatial extent of the deterrence effects. C-POD recordings revealed a significant deterrence effect on harbour porpoises up to 7.5 km away (at about 113 dB re 1 μPa_{rms}), much further than previously reported. During seal scarer operation the number of porpoise detections within 750 m of the C-PODs decreased by between 52% and 95% of the value before the seal scarer was activated. An aerial survey revealed a significant decrease in porpoise density from 2.4 porpoises km^{-2} before to 0.3 porpoises km^{-2} during seal scarer operation within the 990 km^2 study area, showing that the decrease in porpoise detections by passive acoustic monitoring was probably indeed the result of a decrease in porpoise abundance. The results by Brandt *et al.* (2012) highlight the need for caution when applied as a mitigation measure during offshore construction.

Ramp-up / soft-start

A ramp-up scheme or soft-start means that the power source (pile driver) is started in a low-power mode after which the power is increased to a maximum level during a specified time. This time has to be long enough for animals to relocate to a 'safe' distance. It is assumed that animals indeed respond in this manner to the sound, either instinctively or because they have learned to do so. A controlled exposure experiment (3S study) is currently conducted off the Norwegian coast aiming at testing this hypothesis. This study conducted by Miller *et al.* (2012) describes behavioural changes of wild cetaceans observed during controlled exposures of naval sonar. In 2006 through 2009, 14 experiments were conducted with killer (n = 4), long- finned pilot (n = 6), and sperm (n = 4) whales. A total of 14 6-7 kHz upsweep, 13 1-2 kHz upsweep, and five 1-2 kHz downsweep sonar exposures, as well as seven Silent vessel control exposure sessions and eight playbacks of killer whale sounds were conducted. Sonar signals were transmitted by a towable source that approached each tagged subject from a starting distance of 6 to 8 km with a ramp up of source levels (from 152 to 158 to a maximum of 198 to 214 dB re: 1 μPa m). This procedure resulted in a gradual escalation of the sonar received level at the whale, measured by towed hydrophones and by tags that record movement and sound (Dtags). Observers tracked the position of each tagged animal and recorded group-level surface behavior. Two expert panels independently scored the severity of diverse behavioral changes observed during each sonar and control exposure, using the 0 to 9 point severity scale of Southall *et al.* (2007), and then reached consensus with a third-party moderator. The most severe responses scored (i.e., most likely to affect vital rates) included a temporary separation of a calf from its group, cessation of feeding or resting, and avoidance movements that continued after the sonar stopped transmitting. Higher severity scores were more common during sonar exposure than during Silent control sessions. Scored responses started at lower sound pressure levels (SPLs) for killer whales and were more severe during sonar exposures to killer and sperm whales than to long- finned pilot whales. Exposure sessions with the higher source level of 1 to 2 kHz sonar had more changes and a trend for higher maximum severity than 6 to 7 kHz sessions, but the order of the sessions had no effect. This approach is helpful to standardize the description of behavioural changes that occurred during our experiments and to identify and describe the severity of potential responses of free-ranging cetaceans to sonar.

An unwanted side effect of a ramp-up scheme is that it is likely to increase the total duration of an operation, thus increasing also the total acoustic energy transmitted by the source (Ainslie *et al.* 2009). It is possible, however, that a ramp-up procedure is implicit in the normal starting procedure of pile-driving sequence as applied by the offshore constructors anyway. In this case it would be necessary to ensure that the duration, inter-pulse interval and initial level of pile-driving intensity are sufficient to provide a substantial mitigation effect.

5. National Regulations of Impact Pile Driving

Recommendations on Measuring Piling Noise

As required under numerous international, European and national legislations countries have to mitigate to some extent the adverse effects of pile driving, in order to comply with legal commitments. Although substantial gaps in knowledge need to be filled to deal with the impact of anthropogenic sound emitted into the marine environment, several countries established national guidelines related to marine pile driving (see also de Jong *et al.* 2011).

Quantifying the pile driving sound is difficult as the pile penetrates both the water and the seabed, and sound is released into both. The non-linear propagation in both media and the fact that sound even re-enters from the sediment into the water column to some extent, make any calculation highly complex. Recently, two approaches to defining the in-water source level from pile driving have been investigated (de Jong *et al.* 2011):

1. Estimation of an 'energy source level', assuming the pile is a mono-pile sound source within the water column (Ainslie *et al.* 2010); and
2. Characterizing pile driving noise with a numerical model of the environment (water and seabed) and the pile, driven by a force representing the hammer strike (energy and waveform; Zampolli *et al.* 2011).

The first approach is based on underwater sound measurements in the far field of the pile. An acoustic 'far field' is hard to define in shallow water (i.e. in the NCP), where piling occurs, but it is assumed that measurements beyond ten times the water depth from the pile are sufficiently far to be relatively independent of the local details of sound propagation from the pile.

The second approach requires near-field measurements to validate the numerical models and characterize the hammer strikes. Preferably, these are combined with measurements of the dynamic behaviour of the pile material, using strain gauges and accelerometers, according to standard 'Pile Dynamic Analysis' see (ASTM Standard D4945 2008).

As long as different approaches are under development, little consensus is likely to emerge for the standardization of procedures for measurement and analysis of the acoustic source characteristics of pile driving. In the meantime, measurements of received SEL and zero-to-peak SPL at a fixed distance from the pile, *e.g.*, 500 or 750 m, enable direct comparison with available data from wind farms in the North Sea and Baltic Sea (Ainslie *et al.* 2009, Müller and Zerbs 2011).

Despite the complexity of measuring the sound impact of pile driving and the on-going development of approaches for this, several countries are developing guidelines for mitigation measures as an attempt to reduce the adverse effects of pile-driving and other impulsive sounds on marine life.

The Netherlands

Effective legal regulations

The current legislation for activities including offshore pile driving in Dutch waters (NCP) is the 'Waterwet' (Water Law, in effect since 22 Dec 2009) (see below). The permitting process for the construction of wind farms is based on the Dutch 'Natuurbeschermingswet' (Nature Protection Law, revised version came into force 1 Oct 2005), which implements the European Habitats Directive into Dutch national law.

Dutch legislation imposes a strict protection of the harbour porpoise, guided by article 2 of the Habitats Directive asking for a favourable conservation status (FCS). However several geographical discrepancies and a lack of regulations related to mitigate the adverse effects of underwater sound do not facilitate adequate protection.

Water act (Waterwet) - The new Water Act, since December 2009, has created a framework for the modernisation of Dutch water management required for the coming decades. The integration of a number of authorisations will reduce administrative burden for citizens and businesses. Licenses for offshore wind farms fall under the Water Act. Licenses for offshore wind farms require monitoring. An Environmental Impact Assessment (EIA) prior to the license procedure is obligatory. The regulatory body for this is Rijkswaterstaat, Dienst Noordzee, under the Ministry of Economic Affairs (EZ). When the Nature Conservation Act will be extended to the Dutch Exclusive Economic Zone (EEZ) the appropriate authority most likely will be the Ministry of EZ.

Flora and Fauna Act & Nature Conservation Act - In general, Dutch legislation applies to Dutch territory and Dutch territorial waters (to 12 nautical miles offshore). In The Netherlands the harbour porpoise is legally protected under the 1998 Flora and Fauna Act and the 1998 Nature Conservation Act. The harbour porpoise is protected through Article 4, 9, 10 and 11 of the Flora and Fauna Act. It is listed as a species requiring the strictest protection. According to this legislation it is illegal to kill, wound, catch, and obtain protected species, to track them with the above-mentioned intentions, or to disturb them on purpose.

Time closure

Current Dutch regulations restrict pile driving activities for offshore wind turbines on the second half of the year–pile driving is not allowed from 1 Jan to 30 Jun and simultaneous constructions, *i.e.*, pile driving at different sites is not allowed. The required underwater sound measurements as well as the temporal restrictions are a precautionary approach based on concerns about negative effects of the impulsive sound on fish and fish larvae, not on harbour porpoises as in Germany. Until recently for fish larvae no data were available. A first study on sole larvae that only have a very small swimblatter (Bolle *et al.* 2011) revealed no significant effects on sole larvae in this context. Further research has to point out if this is also the case for other species, e.g. with closed or open swimbladder.

Monitoring requirements

As part of the recent permitting process in the Netherlands any applicant is required to conduct a monitoring of the effects of the construction, operation and decommissioning of the wind turbines. The monitoring has to be conducted over a period of at least five years: prior (1 yr), during (1+ yr) and after the construction of wind turbines (3 yrs). A monitoring concept including several taxa, but foremost focusing on marine mammals and birds has to be designed by the applicant which has to be approved and periodically re-evaluated based on the monitoring results by the permitting agency Rijkswaterstaat (RWS). The concept explicitly requires the measurement of underwater sound emissions during construction (*i.e.*, during pile driving), and the modelling of the sound propagation to assess the sound field.

The remaining monitoring requirements focus on the habitat use and migratory movements of harbour porpoises as well as harbour seals and grey seals in relation to the wind farms. Its aim is to detect and quantify the avoidance reactions of harbour porpoises in relation to the pile driving activities during the construction period of the wind farms. The methods to be used following the guideline developed by the permitting agency, Rijkswaterstaat (RWS), include the installation of a network of stationary acoustic monitoring devices (here C-PODs) in combination with frequent, extended ship based visual surveys for marine mammals. The latter should be combined with the use of a towed hydrophone array to increase the chances to detect harbour porpoises.

Alternatively to ship based surveys (including the use of a towed hydrophone array) aerial surveys for marine mammals are carried out now as part of an EIS for the construction of a new wind farm in Dutch waters (K. Lucke, pers. comm., October 2011). These are combined with the use of stationary noise loggers in the vicinity of the pile driving site and in an acoustically unaffected reference site. In order to achieve data on the movements of the seals (which are less likely to be sufficiently detected during visual surveys) telemetry studies on harbour seals have to be conducted. All investigations have to be designed to provide data at a sufficient resolution to yield statistically reliable conclusions.

Cumulative impact

The Dutch regulations are the only ones that consider cumulative impacts from simultaneous construction of wind farms, *i.e.*, pile driving at different sites. However, these regulations only apply to the construction of wind farms while all other offshore construction is not regulated in terms of their acoustic emissions. Furthermore, due to a lack of cross-border spatial planning and international regulatory efforts simultaneous construction activities in Dutch waters and neighbouring areas (Germany, Denmark, Belgium, UK) are not yet considered in the Dutch regulations.

Germany

Effective legal regulations

(excerpts taken from: Bundesamt für Seeschiffahrt und Hydrographie, 2013):

The Bundesamt für Seeschifffahrt und Hydrographie (BSH, Federal Maritime and Hydrographic Agency) is the agency which decides on the approval of offshore wind farm development projects in the German North Sea and Baltic Sea. It carries out the application procedure for wind farms in the German Exclusive Economic Zone. The legal basis for the erection of wind farms in the German EEZ is the United Nations Convention on the Law of the Sea of 10 December 1982 and the German „Seeaufgabengesetz" (Federal Maritime Responsibilities Act), implemented by the „Seeanlagenverordnung" (Marine Facilities Ordinance), which is the basis for the approval procedure. It requires that a wind farm project has to be approved provided that it does not impair the safety and efficiency of navigation, and it is not detrimental to the marine environment.

In the course of the approval procedure, the BSH reviews whether the marine environmental features to be protected (e.g. birds, fish, marine mammals, benthos, sea bottom and water) are put at risk by the project. Besides, offshore wind farm projects comprising more than 20 turbines require an environmental impact assessment based on the UVPG (Environmental Impact Assessment Act). UVPG requires that applicants investigate the marine environment in the project area and predict the impact of the projected wind farm. The BSH has issued regulations specifying the required scope of the investigations to be carried out by the applicants with respect to each of the features to be protected (so-called „Standards for the Environmental Impact Assessment").

As the impact of offshore wind farms on navigational safety and the marine environment has not yet been finally assessed, the BSH so far has only approved pilot-scale projects comprising maximally 80 wind turbines.

Approval procedure for the construction and operation of installations

The construction and operation of installations in the EEZ for commercial purposes are subject to approval by the BSH, in compliance with Art. 2 of the Marine Facilities Ordinance. Approval for a wind farm project will be denied if it poses a threat to the marine environment without there being any suitable measures, either in the form of a time limitation or by imposing requirements, to prevent or compensate the detrimental effects. Under Art. 3 of the Marine Facilities Ordinance, an approval is a non-discretionary administrative act, i.e. in the absence of both of the above reasons for refusal applicants have a legal claim to approval.

An offshore wind farm approval procedure according to the Marine Facilities Ordinance consists of several phases:

Upon receipt of a planning application, it is first checked for completeness. At the same time, in the first round of participation, the competent authorities (including the regional Waterways and Shipping Directorates, mining authority, Federal Environmental Agency, Federal Agency for Nature Conservation) are informed about the project application and asked to comment.

After evaluation of the first comments, a larger number of stakeholders takes part in the second round of participation. It also involves associations (e.g. nature protection, commercial and small craft shipping, fisheries, wind energy associations) and the public, which has the opportunity to inspect the planning documents. Subsequent to the second round of participation, an application conference is held during which the applicant has the opportunity to give a presentation on the project. Conflicting interests and uses are discussed, and the scope of investigations required to study possible effects on the marine environment is determined. On the basis of the environmental studies, the applicant prepares an Environmental Impact Assessment (EIA). A risk analysis dealing with the probability of vessels colliding with wind farm installations is also mandatory.

After having received the documentation from the applicant, the BSH passes it on to the competent authorities and associations, asking them to comment. This is followed by a discussion, during which the comments and information concerning the marine environmental features to be protected, the subject of navigational safety, and other interests and uses are discussed with all stakeholders. Parallel to this, the documents are once more available for public inspection and comment at the BSH.

Then, the BSH reviews whether the requirements for granting approval have been met. An application is considered to meet all requirements for approval when all documents needed for the decision are available to the approval authority. An important part of each approval granted by the BSH for an offshore wind farm is the incidental provisions, which are issued in a largely standardised form. They include, among others, requirements concerning
- use of state-of-the-art methods in the construction of wind turbines, prior to start-up,
- installation of lights, radar, and the automatic identification system (AIS) on the turbines,
- use of environmentally compatible materials and non-glare paint,
- sound reduction during turbine construction and low-noise operation.

Underwater noise exposure criterion

In Germany a noise exposure criterion applies for pile driving activities during the construction of wind farms. This criterion was suggested by the German Federal Environment Agency (Umweltbundesamt, UBA) and recently has been revised (Umweltbundesamt 2011). Like the criteria suggested by Southall *et al.* (2007), the UBA criterion is a dual criterion and aims for the protection of harbour porpoises from TTS. Harbour porpoises are of all the marine species in German waters considered most sensitive to sound, although UBA is anticipating also to protect all other, less sensitive species. The UBA criterion is based on the results from Lucke *et al.* (2009) who measured TTS in a harbour porpoise after exposure to single impulsive underwater signals at levels above 164 dB re 1 μPa^{2}s SEL and 200 dB re 1 μPa peak

SPL. Based on these results, and with an additional safety margin, the UBA has set the noise exposure criterion to an SEL of 160 dB re 1 $\mu Pa^2 s$ and a peak SPL of 190 dB re 1 µPa. The safety margin is included to account for variability among individual animals and uncertainties with regard to the cumulative effect of multiple exposures (which likely lead to lower threshold values). The value is not to be exceeded at a distance of 750 m from the sound source. At closer range operators must apply a sensible set of measures to ensure that no harbour porpoise (or any other marine mammal) is within this perimeter. Up to now there is no standard procedure to determine source levels for a structure such as the pile of a wind turbine which emits sounds over the entire water column as well as within the media above and below (air and ground). By relating the noise exposure criterion to a distance of 750 m, where sound levels can be determined unequivocally, UBA prevents possible errors in measuring or calculating the near field sound levels in such a complex scenario.

However, simulations revealed that the UBA criterion would be sufficient only for animals avoiding the area at high swimming speeds while mother-calf pairs *e.g.*, which cannot swim at high speeds or cannot maintain those speeds over an extended period would be exposed to cumulative levels above the UBA criterion. Moreover, UBA stated that this criterion does not account for behavioural effects and/ or population level effects. Hence, like other criteria (JNCC 2010a, Southall *et al.* 2007), the UBA states that its criterion is to be regarded as an interim criterion and it will be revised as new relevant information becomes available. As a consequence UBA suggests considering temporal and/or spatial restrictions for pile driving activities in sensitive areas and/or periods.

Upon publication of TTS results from harbour porpoises by Lucke *et al.* (2009), the levels determined in this study were adopted by the BSH. Thereafter, operators have applied quieter construction techniques and/or sound mitigation methods (both discussed in chapter 4). to meet the noise exposure criterion. As the noise exposure levels remain unchanged in the revised version of the UBA criterion, the levels requested by the BSH will stay unchanged.

United Kingdom

There are no specific regulations for pile driving in the United Kingdom (UK). However, the construction of offshore wind turbines, which usually involves pile driving, is regulated in the UK with regard to noise monitoring and mitigation.

<u>Effective legal regulations:</u>

- FEPA (Food and Environmental Protection Act 1985)
- Joint Nature Conservation Committee protocol (JNCC 2010a), consolidating all the various amendments made to the Conservation Regulations 1994 (*i.e.*, the Habitats Regulations, HR) in respect of England and Wales
- Offshore Marine Conservation (Natural Habitats) Regulations 2007 (the Offshore Marine Regulations, OMR) 2007
- Coast Protection Act 1949 (CPA, Section 34); despite some differences in legal aspects, data requirements for CPA and FEPA are for all intents and purposes identical.

<u>Offshore pile driving guidelines:</u>

The JNCC has issued guidelines specifically dealing with offshore pile driving (JNCC 2010b). They state:

> *Pile driving in the marine environment without mitigation is likely to produce noise levels capable of inducing adverse avoidance reactions at a considerable distance from the activity, which could constitute disturbance under the Regulations (HR and OMR depending on the area). Pile driving is also likely to cause injuries (e.g., hearing impairment) and there remains the possibility of causing death in marine mammals that are in very close proximity.*

This protocol does not document measures to mitigate disturbance effects, but has been developed to reduce to negligible levels the potential risk of injury or death to marine mammals in close proximity to piling operations.

If the risk of disturbance cannot be avoided or reduced to negligible levels, the developers need to obtain a license under regulations 53/49 (HR/OMR respectively) in order to avoid the application of regulations 41(1)(b) and 39(1)(b) of the HR/OMR.

There will be future updates to the 2010 pile driving guidelines, but no changes are expected soon/ in near future.

Denmark

Permits for building offshore wind turbines in Danish waters are regulated by the Danish Energy Agency (DEA). The only environmental requirement enforced by the DEA with regard to pile driving activities is the use of acoustic deterrent devices (pingers and seal scarers) before the start of activities (M. Cramer Buch, DEA, pers. comm., January 2013). Furthermore, it is unlikely that a publicly funded monitoring programme for large scale environmental monitoring will be reissued. However, if an individual offshore wind farm needs a monitoring programme, this will be established most likely at the expense of the owner

Sweden

Offshore pile driving is regulated in Sweden by the Environmental Code (Regeringskansliet 2000). The only environmental concern is that marine pile driving not be detrimental to fishing. Pile driving operators therefore must "at their own expense, make and in future maintain any arrangements that are necessary for the passage of fish or the sustainability of fishing, […] comply with any other conditions that may be necessary in the context of the operations to protect fishing in the water in which the water operations are carried on or in adjacent water areas. If the benefit of a disputed installation or a condition cannot reasonably be considered to justify the expense incurred by the operator for compliance, the operator may be discharged from such an obligation." (Regeringskansliet 2000).

New regulations to better address noise related effects on the marine environment are being discussed and will be regulated by the Swedish Authority for Marine and Water Management.

Ireland

There are no current specific regulatory requirements to reduce or mitigate the effects of pile driving in Irish waters enforced yet (P. Scorey, NOW Ireland, pers. comm., February 2013). However in March 2012 the Irish government drafted guidelines which have gone through public consultation, but which are not implemented yet (www.npws.ie). These guidelines recommend a risk assessment for anthropogenic sound-related impacts on relevant protected marine mammal species. Such an assessment should consider direct, indirect and cumulative effects of anthropogenic sound. In relation to specific maritime sound-producing operations or activities at sea, technical guidance has been developed recommending to extend the use of MMOs for mitigating the acoustic impacts of a range of activities including pile driving.

Belgium

To build a wind farm in Belgium, various permits must be obtained, including an environmental permit for the construction and the exploitation of the farm. This legislation includes an environmental impact assessment (EIA) by MUMM. The EIA is based on an environmental impact study (EIS) submitted by the applicant. In the framework of its evaluation the MUMM can, if necessary, carry out, or order additional studies and research.

There is also a public consultation organised during 45 days and if impacts could cross international borders, consultation with the concerned country is arranged. Based on this EIA and on the results of the public consultation, the MUMM advises the federal Minister responsible for the marine environment. In this advice the MUMM gives an opinion on the acceptability of the project concerning the marine environment and on the conditions, which the project must fulfil to be acceptable. The Minister decides whether the environmental permit should be granted. For every new permit the conditions might be different, based on latest scientific data. (J. Haelters, pers. comm., December 2012).

The use of at least one Acoustic Deterrent Devices (ADD) (pinger or seal scarer) with a source level of 170 to 195 dB re 1µPa is required; it should start working 1 hour before the start of piling until pile driving has started, at a distance of at the most 200 m from the piling location.

Moreover, a soft-start procedure is taken up in the permit – it is however not standardized. The most recent conditions require a maximum energy output of the piling hammer at least 10 minutes after the first stroke. The soft-start procedure has to be agreed upon by MUMM as well.

There are currently seasonal restrictions: no piling between 1 January and 30 April, given that this is the period with the highest density of harbour porpoises in Belgian waters.

However, the requirements for offshore wind farms in Belgian waters have been repeatedly adapted and vary between the different wind farms (Beheerseenheid van het Mathematisch Model van de Nordzee, 2013). The current status of all requirements is provided under:
http://www.mumm.ac.be/NL/Management/Sea-based/windmills_docs.php.

Unites States of America

In the USA, the Marine Mammal Protection Act (MMPA, Daly et al., 2012) aims to protect some marine mammal taxa, i.e. cetaceans, phocids (true seals) and otariids (eared seals), but not sirenians (manatees and dugongs), mustelids (sea otters) or ursids (polar bears) from anthropogenic noise, and the Endangered Species Act (ESA) does the same for turtles. Ainslie (2012) provides an excellent overview of the current legislation on noise exposure in the U.S.A.

A 'take' is defined under the MMPA as to harass, hunt, capture, kill, or collect, or attempt to harass, hunt, capture, kill, or collect. Under the ESA, 'to take' means to harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or to attempt to engage in any such conduct. Under the 1994 Amendments to the MMPA, 'harassment' is statutorily defined as any act of pursuit, torment or annoyance which has the potential to injure a marine mammal or marine mammal stock in the wild (Level A harassment), or which has the potential to disturb a marine mammal or marine mammal stock in the wild by causing disruption of behavioural patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering, but which does not have the potential to injure a marine mammal or marine mammal stock in the wild (Level B harassment).

Authorisation for incidental 'takings' may be granted if the National Marine Fisheries Service (NMFS) finds that the taking will have a 'negligible' impact on animal populations, and if the permissible methods of taking and requirements pertaining to the mitigation, monitoring, and reporting of such taking are set forth (NMFS 2008). The impact is 'negligible' if the proposed activity is not reasonably likely to adversely affect the population through effects on annual rates of recruitment or survival. NMFS publishes in the Federal Register a notice of a proposed Incidental Harassment Authorization (IHA) or a notice of receipt for a request for the implementation of regulations governing the incidental taking. Information gathered during the associated comment period is considered by NMFS in developing, if appropriate, IHAs and regulations governing the issuance of Letters of Authorizations (LOAs) for the proposed activity.

The NMFS policy is under review. It currently states that cetaceans and pinnipeds should not be exposed to pulsed sounds exceeding 180 and 190 dB_{rms} re 1 μPa, respectively (NMFS 2000, see also Ainslie 2012). The general assumption is that animals will be behaviourally 'harassed' (Level B) at levels above 160 dB_{rms} re 1 μPa. NMFS generally requires that pile driving cease if a cetacean enters the 180 dB_{rms} re 1 μPa isopleth (190 dB_{rms} re 1 μPa for phocids and otariids) which represents the onset of injurious harassment (Level A). All levels are applied without any weighting. It is interesting that – as stated by Ainslie (2012) "NMFS assumes an "effective quiet" if the SEL from a single strike is less than 150 dB re 1 $μPa^2$ s. Strikes below this level are assumed not to contribute to the risk of injury, irrespective of the number of strikes, and are not included in the calculation of the cumulative SEL for the purpose of impact Assessment".

Vibratory pile driving is considered to be a source of continuous sound, for which NMFS applies different noise exposure criteria: the threshold for Level B harassment is set to 120 dB_{rms} re 1 μPa while the thresholds for Level A harassment are identical to the impulsive sounds.

However, as the US National Marine Fisheries Service (NMFS) policy is under review, they are in the process of updating the National Atmospheric Administration (NOAA) Acoustic Guidelines for Assessing Impacts of Anthropogenic Sound on Marine Mammals based on current new results/ literature.

6. Existing scientific advice on setting exposure criteria

The aim of implementing noise exposure criteria into offshore marine regulations is to prevent negative effects to marine fauna from exposure to intense anthropogenic sounds. This implies that all species at risk should be equally protected from auditory damage if these criteria are to be enforced. The biggest deficit, however, is the current lack of data on auditory sensitivity and tolerance to intense sound in many marine species. Most data on TTS have been measured in only a small number of marine mammal species, and the data indicate substantial differences with regard to hearing sensitivity and vulnerability to TTS between functional groups (species using high-frequency echolocation signals *vs.* species emitting mid-frequency signals, as stated above). Consequently, any noise exposure criterion may be effective only if it is based on data from the 'most sensitive' species occurring in the area of concern.

Because sound propagates through water in a non-linear fashion, the sound received by an animal depends not only on the acoustic characteristics of the sound source, but also on the receiver's position relative to the sound source and on the oceanographic characteristics (bathymetry, sound speed profile, *etc.*) of the area. While some noise exposure criteria (*e.g.*, in the USA) consequently focus on the received sound levels, other regulations include a stand-off distance from the sound source where the noise exposure criterion must be met at its perimeters (*e.g.*, Germany).

Based on a review of literature on marine mammal hearing as well as physiological and behavioural responses to anthropogenic sound, Southall *et al.* (2007) proposed initial injury criteria for marine mammals, based on the peak SPL and SEL metrics. These criteria account for the type of sound (non-pulse, single-pulse, or multi-pulse), as well as the approximate ranges of hearing frequency of the mammals involved. Marine mammal species were assigned to one of five functional hearing groups: low-, mid-, and high-frequency cetaceans, as well as pinnipeds listening in water and in air. The harbour porpoise is considered a high-frequency cetacean.

The Southall injury criteria are for the onset of PTS in marine mammals. They are dual criteria, in that if either criterion is exceeded, injury is assumed. The peak SPL criteria are unweighted, whereas the SEL criteria are frequency weighted for the relevant functional hearing group (known as M-weighting).

The proposed exposure criteria for injury were derived from measured or assumed TTS-onset thresholds for each hearing group plus TTS growth rate estimates, although data were limited to few species. Available TTS data for two mid-frequency cetacean species (bottlenose dolphin, *Tursiops truncatus* and beluga, *Delphinapterus leucas*) and three pinniped species (harbour seal, *Phoca vitulina* and California sea lion, *Zalophus californianus*, and northern elephant seal *Mirounga angustirostris*) were used as the basis for estimating PTS-onset thresholds (Table 1).

Table 1: Proposed injury and behavioural disturbance threshold criteria for individual marine mammals exposed to 'discrete' noise events, either single or multiple exposures within a 24 h period (Southall et al. 2007, p. 443, 452). Non-pulses are defined as pulses that have travelled long distances and lost their impulsive characteristics, such as fast rise times.

Marine mammal group	Injury			Behavioural disturbance
	Single pulses	Multiple pulses	Non-pulse	Single pulses
High-frequency cetaceans				
unweighted peak SPL (dB re 1 μPa)	230	230	230	224
M-weighted SEL (dB re 1 $\mu Pa^2 \cdot s$)	198	198	215	183
Mid-frequency cetaceans				
unweighted peak SPL (dB re 1 μPa)	230	230	230	224
M-weighted SEL (dB re 1 $\mu Pa^2 \cdot s$)	198	198	215	183
High-frequency cetaceans				
unweighted peak SPL (dB re 1 μPa)	230	230	230	224
M-weighted SEL (dB re 1 $\mu Pa^2 \cdot s$)	198	198	215	183
Pinnipeds (in water)				
unweighted peak SPL (dB re 1 μPa)	218	218	218	212
M-weighted SEL (dB re 1 $\mu Pa^2 \cdot s$)	186	186	203	171

** All SPL injury criteria are based on the peak pressure known or assumed to elicit TTS-onset, plus 6 dB. SEL injury (PTS) criteria are based on the SEL eliciting TTS-onset plus (1) 15 dB for any type of marine mammal exposed to single or multiple pulses, (2) 20 dB for cetaceans or pinnipeds in water exposed to non-pulses, or (3) 13.5 dB for pinnipeds in air exposed to non-pulses.*

† Behavioural response criteria are based on (1) results for beluga TTS-onset thresholds for cetaceans, and (2) estimates of TTS-onset for pinnipeds.

Based on extrapolation of available data, Southall *et al.* (2007) suggest slightly lower estimates of TTS onset for harbour porpoises compared to mid-frequency cetaceans, may be warranted for high-frequency cetaceans exposed to very high-frequency sounds (≥ 100 kHz).

The equal energy hypothesis states that two sounds with equal energy are equally harmful (with the exception of extreme impulse sound, which can induce rupture of the tympanic membranes and fracture of the ossicular chain). This implies that TTS data obtained from studies of impulsive signals could be used to predict effects from exposure to longer lasting sounds. Several well-controlled TTS studies on marine mammals provide data supporting this hypothesis, and most regulations regarding underwater sound exposure have successively applied the so-called dual criteria of peak SPL and SEL as suggested by Southall *et al.* (2007, see also Umweltbundesamt 2010).

There seem to be substantial differences in the tolerance of the auditory system to intense impulsive sound between the functional classes suggested by Southall *et al.* (low-, mid- and high-frequency echolocators) as a study on harbour porpoises (Lucke *et al.* 2009) revealed. The TTS limit for this high-frequency echolocator species was found to be at 200 $dB_{peak-peak}$ re 1 μPa or a SEL of 164 dB re 1 $\mu Pa^2 s$ for exposures to single impulses. This clearly indicates that a group- or even species specific difference has to be taken into account for the noise exposure criterion.

The criteria suggested by Southall *et al.* (2007) are based on PTS and levels are thus higher than what others have suggested. Nevertheless, modelling of cumulated sound exposure over the duration of a single pile driving event suggests that levels sufficient to elicit PTS could be reached for both seals and porpoises at distances of around 1 km from the piling site (Brandt *et al.* 2011). For this reason mitigation measures in the form of soft-start/ ramp-up procedures and use of acoustic deterrent devices (pingers and seal scarers) immediately before piling have been introduced in order to deter animals out of the impact area before piling commences.

Gordon *et al.* (2010) modelled the cumulated sound exposure for seals and porpoises during pile driving where both acoustic deterrent devices and a soft start procedure were used. In their model the animals were allowed to swim in a straight line away from the piling site whenever they were exposed to the acoustic deterrent device and hence reduce received sound pressure levels. Even under this scenario animals which started out close to the piling site received cumulated exposure exceeding PTS thresholds. The ‘safe range’, which is the start distance for the animals where they could escape without exceeding PTS-thresholds varied with pile diameter, transmission loss model, escape speed and species (harbour seal, *Phoca vitulina*, or harbour porpoise, *Phocoena phocoena*). With realistic values their modelling suggests that even animals located several kilometres from the piling site at onset of mitigation may be at risk for exceeding PTS-thresholds. The exposure criteria of Southall *et al.* (2007) did not include information about harbour porpoises as this was not available at that time. When Gordon *et al.* (2010) used the thresholds of Lucke *et al.* (2009) in the model, the ‘safe distance’ increased to ~10 km.

7. International regulation on impact of pile driving

Europe

In the European Union, anthropogenic ocean noise is now considered a form of pollution that, depending on source and intensity, may degrade habitat and have adverse effects on marine life ranging from disturbance of communication or group cohesion to injury and mortality. Underwater noise has been listed as one of 11 descriptors for the assessment of a good environmental status (GES) of the European waters under the European Marine Strategy Framework Directive (MSFD). Most European countries bordering the sea have little or no regulation of anthropogenic offshore activities with regard to underwater sound emissions.

European Recommendations, Guidelines, Regulations for Marine Pile Driving

Most regulations regarding sound emissions from marine pile driving have been implemented in the context of offshore wind farms. Therefore, most of the relevant literature (for a review see ICES 2010; aspects relevant to pile driving cited below) deals with the effect of pile driving during construction of offshore wind turbines. National and international guidelines and regulations exist for monitoring and mitigation of the effects of offshore wind farms.

Environmental Impact Assessment Directive

In European waters, for most offshore construction activities, an environmental impact assessment (EIA) must be carried out. The EIA Directives on Environmental Impact Assessment of the effects of projects on the environment (Directive 85/377/EEC 1985, amended 1997/2003 and Directive 97/11/EC) set out rules on what information an EIA must provide to comply. The development of common guidelines for mitigation in relation to acute noise sources is highly recommended. Increased cooperation between EU Member States will be required by the MSFD through the application of an ecosystem-based approach to the management of human activities.

European Habitats Directive

Under the European Habitats and Species Directive (92/43/EEC) the Harbour Porpoise has been awarded the highest protective status as it is listed on Annex II (species for which protected sites need to be selected by Member States conserving their habitats) and IV (species that have to be strictly protected) of the EU Habitats and Species Directive (92/43/EEC). The EU Habitats and Species Directive is relevant in the framework of offshore wind farms and marine pile driving in several aspects. The Habitats Directive requires that Member States undertake surveillance of the conservation status of species of Community interest, with the aim to maintain or restore species at a Favourable Conservation Status (FCS). The conservation status of species will be taken as 'favourable' when: (a) population dynamics data on the species concerned indicate that it is maintaining itself on a long term basis as a viable component of its natural habitat; (b) the natural range of the species is neither being reduced nor likely to be reduced for the foreseeable future; and (c) there is, and will probably continue to be, a sufficiently large habitat to maintain its populations on a long term basis. The protection of cetaceans from the impact of anthropogenic noise can form part of the strict protection awarded to them. There is increasing consensus on the view that noise should be considered a form of pollution and is covered in general terms in current international legislation regulating the emission of energy into the marine environment. According to this generally accepted view deliberate or incidental emission of noise is clearly an issue in cases where it would likely be significant in relation to the objectives of the Directive, which include the maintenance of the protected species at a favourable conservation status.

European Integrated Maritime Policy

One of the products of the European Integrated Maritime Policy, launched by the European Commission in October 2007, is the Roadmap for Maritime Spatial Planning: achieving common principles in the EU. According to Gilliland and Laffoley (2008), marine spatial planning is an essential tool for conducting ecosystem-based sustainable development of the marine environment. One of the applications mentioned in the EU Directive 2002/49/EC for noise in air is generating strategic noise maps, which are useful for spatial planning in relation to sound exposure.

Marine Strategy Framework Directive

The change in paradigm of the European Union water policy started with the Water Framework Directive (2000/60/EC, WFD) and was followed by the Marine Strategy Framework Directive (MSFD; EC MSFD 2008/56/EC). One of the main objectives of the MSFD is to achieve a Good Environmental Status (GES) for European marine waters by 2020. The MSFD obliges every member state to achieve or maintain good environmental status, under which also the introduction of energy including underwater noise is considered a main concern (Tasker *et al*., 2010). While developing a framework for underwater noise for the implementation of the MSFD, noise mapping on a regional basis should be used to analyse noise budgets of the oceans and regional sea areas. These directives changed Europe from a sectorial to a holistic approach, which accounts for the synergistic and cumulative effects of different anthropogenic pressures on the marine environment. For achieving GES, eleven descriptors were provided, including Descriptor 11, which states that "introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment." Two indicators for Descriptor 11 are identified. Proposed Indicator 1 deals with the registration of the distribution in time and place of loud, low- and mid-frequency impulsive sounds; Indicator 2 demands measurements on continuous low-frequency sound.

As recognized and suggested in the process of developing the framework for underwater noise for the implementation of the MSFD, regional noise mapping should be used to analyse noise budgets of the oceans and regional sea areas. This can be done by acoustic measurements and modelling based on data and information gained through the application of the suggested indicators for Descriptor 11:

> ***Indicator 1****: Distribution in time and place of loud, low and mid frequency impulsive sounds*
>
> *Proportion of days and their distribution within a calendar year over areas of a determined surface, as well as their spatial distribution, in which anthropogenic sound sources exceed levels that are likely to entail significant impact on marine animals measured as Sound Exposure Level (in dB re 1μPa^{2}s) or as peak sound pressure level (in dB re 1μPa peak) at one metre, measured over the frequency band 10 Hz to 10 kHz.*
>
> ***Indicator 2****: Continuous low frequency sound*
>
> *Trends in the ambient noise level within the 1/3 octave bands 63 and 125 Hz (centre frequency) (re 1μPa RMS; average noise level in these octave bands over a year) measured by observation stations and/or with the use of models if appropriate.*

In 2010 the European Commission decided that guidance was needed to help Member States implement the indicators under descriptor 11. A technical working sub-group (TSG Noise) focussed on clarifying the purpose, use and limitation of the indicators and described methodology that would be unambiguous, effective and practicable. For both the impulsive and ambient noise indicators it has been possible to make significant progress towards practical implementation of the indicators, and most ambiguities have been solved (Van der Graaf *et al*. 2012)

Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish, and North Seas

The parties to the Agreement on the conservation of small cetaceans of the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS) have prepared several Resolutions with recommendations on underwater noise. In the Resolution on Adverse Effects of Underwater Noise on Marine Mammals during Offshore Construction Activities for Renewable Energy Production, adopted by ASCOBANS Parties in 2009, parties recommend that:

- A strategic approach in marine renewable developments should be taken;
- The precautionary approach should be followed;
- Guidelines should include an appropriate location of devices; measures for avoiding construction activities with high underwater noise source levels during the periods of the year with the highest densities of small cetaceans; measures for avoiding construction activities with high underwater noise source levels when small cetaceans are present in the vicinity of the construction site; measures for alerting small cetaceans to the onset of potentially harmful construction noise; and technical measures for reducing the sound emission during construction works.

ASCOBANS further promotes the development of effective mitigation measures, guidelines and technological adaptations, an assessment of the effectiveness of guidelines, a continued monitoring of effects and the exchange of information.

Agreement on the Conservation of Cetaceans in the Black Sea, Mediterranean Sea, and contiguous Atlantic area

For the waters of the Mediterranean and Black Seas the potential impact of noise on the marine environment, especially on cetaceans, is regulated by the Agreement on the Conservation of Cetaceans in the Black Sea, Mediterranean Sea and contiguous Atlantic area (ACCOBAMS). ACCOBAMS aims to reduce threats to cetaceans in Mediterranean and Black Sea waters and improve the knowledge of these animals. It was concluded in the auspices of the Convention on Migratory Species in 1996 and entered into force in 2001.

On request by the ACCOBAMS Secretariat, Pavan (2006) provided a concise summary of guidelines for setting up a permit system to regulate acoustic pollution that could threaten marine mammals in the Agreement Area. The ACCOBAMS Scientific Committee had noted that:

- Noise is a significant threat to marine mammals and other marine wildlife;
- Underwater noise should be regulated and reduced;
- Underwater noise should be included in Environmental Assessments; and
- Underwater noise levels should be considered a quality parameter when assessing habitats, MPAs (*Marine Protected Areas*) and other issues related to marine life.

Pavan (2006) stated:

> *In the absence of specific laws, and given the fact that underwater noise is a transboundary pollutant, in the Mediterranean waters the EU Habitat Directive is probably the best framework for developing a permit system that complies with the opinions expressed by international organizations (ACCOBAMS Recommendation 2.7 and ACCOBAMS Resolution 2.16, the recommendations of the 56° and 58° IWC meetings (held in 2004 and in 2006), and the European Parliament Motion B6-0089/04).*
>
> *The European Union Habitat Directive states that it is not permissible to deliberately disturb in the wild, any creature which is enlisted in Annex IV (a), where all Cetaceans (and several other marine mammals) are listed. In addition to species protection, the Habitats Directive*

also makes provision for the site-based protection of a range of marine mammal species (listed in Annex II), including bottlenose dolphins and harbour porpoises and all species of seal. To achieve this, Special Areas of Conservation (SAC), as well as Marine Protected Areas (MPA) should be proposed and designated as key tools for marine mammals' protection.

According to Pavan (2006) construction/demolition works on harbours/coast, including pile drivers, jack hammers, *etc.*, are activities to be taken into consideration within the context of the ocean noise issue and a permit request should be submitted to a designated Agency. However, no guidelines have yet been implemented and no agency has been designated responsibility for granting these permits.

Convention for the Protection of the Marine Environment of the North-East Atlantic

Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention) recognized noise as a form of pollution in 2004, which was confirmed by the OSPAR-Commission in 2005. OSPAR (2009) states:

It is currently difficult to provide an evaluation of the effectiveness and adequacy of the measures taken and planned for the protection of the marine environment against effects from underwater noise. In order to improve our understanding of the effects of underwater sound on marine life, research including behavioural and auditory studies, monitoring of the distribution (both of the noise sources and of relevant species), and investigation of anthropogenic sound budgets will be needed.

Furthermore, there is an urgent need for standardization of methodologies to study the impact of sound on marine species over larger spatial scales. Increased efforts should be made to develop and apply effective mitigation measures to reduce the impacts of underwater noise (of any source) on marine life. The most effective mitigation measures are geographical and seasonal restrictions to avoid ensonification of sensitive species and habitats. Sound-producing activities may be designed to avoid areas and/or times where/when sensitive marine mammals and other species are usually engaged in susceptible activities such as mating, breeding, feeding, or migration.

In a background document (OSPAR 2009) the effects of offshore pile driving on marine fauna are discussed along with other marine construction and industrial activities.

North Atlantic Treaty Organization

In reaction to a series of mass strandings of cetaceans, mostly beaked whales, which have been linked to military sonar operations (Simmonds and Lopez-Jurado 1991, Frantzis 1998, NOAA and US Navy 2001, Jacobs and Hall 1972, Fernández *et al.* 2005), the North Atlantic Treaty Organization (NATO) has developed and implemented regulations with regard to intense acoustic emission from vessels, especially with respect to the operation of Low and Mid-Frequency Active Sonar (LFAS/MFAS) systems operated by the NATO Undersea Research Centre (NURC).

Even though LFAS und MFAS signals are not considered impulsive sounds, but transient tonal sounds, the NURC guidelines are listed here as numerous studies on the effects of noise on marine mammals have been funded over the past decades by the Office of Naval Research. The results of these studies were partially implemented into the NURC guidelines.

The NURC Staff Instruction 77 (SI-77) is updated continuously (*e.g.*, within the Marine Mammal Risk Mitigation Project, NURC 2006) and comprises procedures and marine mammal risk mitigation protocols. The guideline requires an Environmental Scoping Study (ESS), mitigation procedures, and monitoring together with an associated audit trail. An important basis for the ESS is spatial modelling to predict areas of primary importance for marine mammals. Specific prediction tools like SAKAMATA (TNO, The Netherlands) have been developed to help sonar operators to check which marine mammals are likely to be in the operating area and how sensitive their hearing is. The advice from this program includes a 'ramp-up scheme' that accounts for the sonar specifications, the environmental conditions, and the types of marine mammals present in the operating area. Using a ramp-up gives marine mammals the opportunity to seek quieter areas during sonar operations.

8. International Conventions and Agreements on the Effects of Underwater Sound

Convention on Migratory Species

The Convention on Migratory Species (CMS) Resolution 9.19 (UNEP/CMS 2009), on adverse anthropogenic marine/ocean noise impacts on cetaceans and other biota, noted that in case of doubt the precautionary approach should be applied. Parties are further encouraged to facilitate:

- Regular collaborative and coordinated temporal and geographic monitoring and assessment of local ambient noise (both of anthropogenic and biological origin);
- The compilation of a reference signature database, to be made publicly available, to assist in identifying the source of potentially damaging sounds;
- Characterization of sources of anthropogenic noise and sound propagation to enable an assessment of the potential acoustic risk for individual species in consideration of their auditory sensitivities; and
- Studies reviewing the potential benefits of 'noise protection areas', where the emission of underwater noise can be controlled and minimized for the protection of cetaceans and other biota.

United Nations

Resolution A/RES/60/30 (2005) of the United Nations adopted by the General Assembly on March 8 2006, Paragraph 84 demands further studies and consideration of the impacts of ocean noise on marine living resources.

International Union for Conservation of Nature

The International Union for Conservation of Nature states that, when there is a reason to expect that harmful effects on biota may be caused by such ocean noise, lack of full scientific certainty should not be used as a reason for postponing measures to prevent or minimize such effects (UNEP/CMS 2009).

International Whaling Commission

Resolution 1998-6 of the International Whaling Commission (IWC) identified the impacts of anthropogenic noise as a priority topic for investigation within its Scientific Committee, and that the Scientific Committee, in its report to the 56th meeting of the IWC, concluded that military sonar, seismic exploration, and other noise sources such as shipping pose a significant and increasing threat to cetaceans, both acute and chronic.

United Nations Environment Programme

The United Nations Environment Programme (UNEP) recognizes the lack of data on the distribution and migration of some populations of migratory cetaceans and the adverse human-induced impacts on cetaceans (UNEP/CMS 2009). Therefore, the Conference of the Parties to the Convention on the Conservation of Migratory Species of Wild Animals urged Parties and invited non-Parties to endeavour to control the impact of emission of man-made noise pollution in habitats of vulnerable species and in areas where marine mammals or other endangered species may be concentrated, and where appropriate, to undertake relevant environmental assessments on the introduction of systems which may lead to noise associated risks for marine mammals.

United Nations Convention on the Law of the Sea

The fundamental obligation to protect and preserve the marine environment is reflected in Part XII of the United Nations Convention of the Law of the Sea (UNCLOS). Article 194 (1) obliges parties to take measures that are necessary to prevent, reduce, and control pollution of the marine environment from any source using the best practicable means at their disposal and in accordance with their capabilities. Pollution is broadly defined in Article 1 (4) and includes the term 'energy'. As interpreted in accordance with its ordinary meaning in the context of the objects and purposes of UNCLOS, energy should encompass noise within its remit. According to Art 208 (1) and (2) under part XIII of UNCLOS, all activities relating to the exploitation and exploration of the seabed must be carried out with due regard to the protection of the marine environment and, in particular, the prevention and control of pollution. Accordingly, parties must take measures to prevent and control the emission of noise associated with seismic surveys, drilling, pile driving, and other associated activities. Article 211 of UNCLOS seeks to prevent, reduce, and control the pollution of the marine environment from vessels.

Helsinki Convention

Regulation 2 of Annex VI of the 1992 Helsinki Convention on the Protection of the Marine Environment Area (HELCOM) stipulates that parties must use the best available technology and best environmental practice to prevent and eliminate pollution, including noise, from offshore activities.

European Science Foundation

In a position paper (Boyd *et al.* 2008), the European Science Foundation (ESF) lists pile driving as a type of anthropogenic sound source that could affect marine mammals. The effects of greatest concern caused by pile driving are physical trauma, hearing loss, behavioural change, and behaviourally-mediated effects (see Nowacek *et al.* 2007). Within its 'Risk Assessment Framework' the ESF applies a five step analytical process consisting of hazard identification, dose-response assessment, exposure assessment, risk characterization, and risk management. An important aspect of the risk assessment is to question if the effects of anthropogenic sound on marine mammals result in changes in species viability. This aspect is dealt with in the Population Consequences of Acoustic Disturbance (PCAD) model (Figure 3) presented in the US National Research Council (NRC) report (National Research Council 2005). This model provides a rationale for prioritization of research. It is represented by a flow diagram showing research topics in areas ranging from sound production, through behaviour change and effects on life function, to impacts on vital rates, and by implication, the effects on populations. To construct a full risk assessment, it is necessary to make the linkages among each of these aspects.

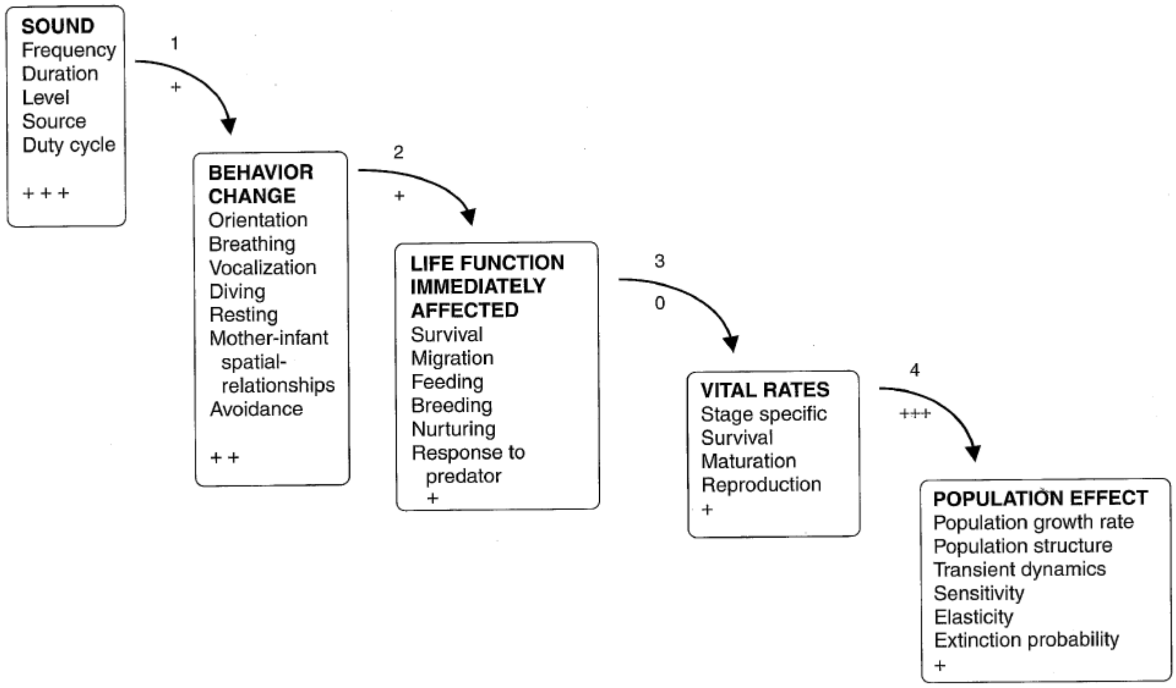

Figure 3: The conceptual Population Consequences of Acoustic Disturbance (PCAD) model describes several stages required to relate acoustic disturbance to effects on marine mammal population (from: National Research Council 2005).

Following this model it is an extremely complex process to translate behavioural changes into population level effects. Current data are insufficient to allow the PCAD model to serve as more than a conceptual model (National Research Council 2005). Recently studies on Elephant seals (Mirounga angustirotris) provided for the first time sufficient data to develop a bioenergetics approach to parameterize the transfer functions developed in the PCAD model.

This approach allowed to identify species and/or particular life history characteristics that are likely to be sensitive or resilient to acoustic disturbance (Costa *et al.* 2011). The problem is that such data are not available for other species, including the harbour porpoise.

In order to assess the potential effects on e.g. harbour porpoises a simpler, mechanistic model was developed which provides a mechanistic approach to predict potential impact of offshore activities. This model, named "Population Consequences of Disturbance" (PCOD) model (Figure 4), can therefore be integrated as part of an adaptive management scheme to advise on future anthropogenic use/ future detonations of underwater explosives (Lusseau *et al.* 2012).

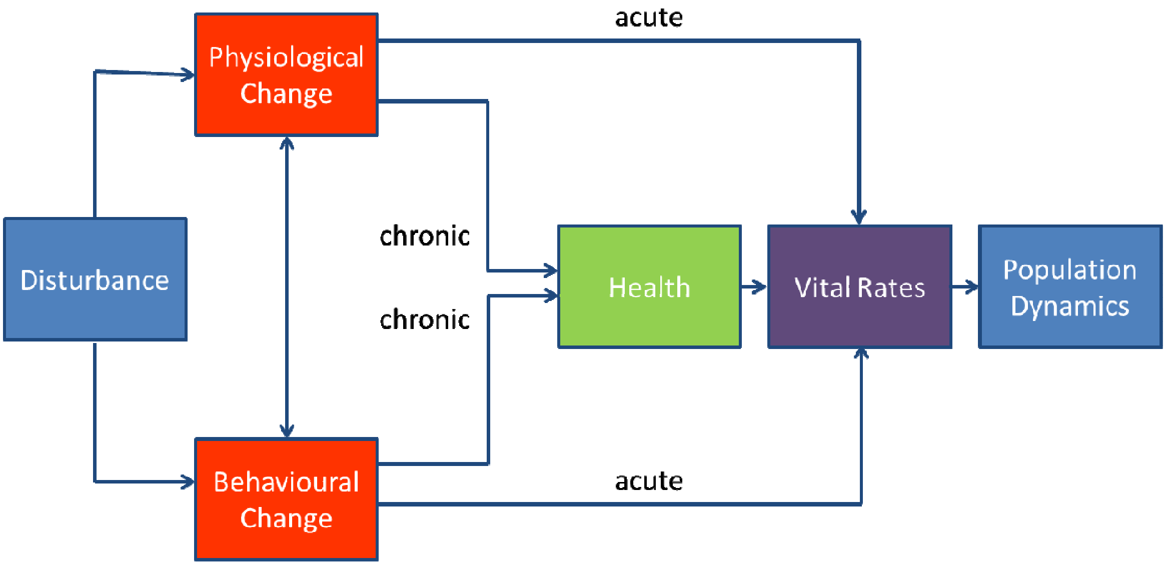

Figure 4: The PCOD framework for modelling the population consequences of disturbance developed by the ONR working group on PCAD (Anon. 2012). The term "Health" is used to describe all aspects of the internal state of an individual that might affect its fitness. These include, for example, the extent of its lipid reserves and its resistance to disease. "Vital rates" refers to all the components of individual fitness (probability of survival and producing offspring, growth rate, and offspring survival).

9. Monitoring and Mitigation

Daly et al. (2012) state that one of the most effective methods to reduce noise exposure-related impacts to marine mammals is spatial and/or temporal limitation of the activity where practicable. The authors refer to other mitigation measures as delay of source start-up or shutdown if a marine mammal enters into a designated zone of exposure, source ramp-up to allow individual time to leave the area before full power is reached, and they refer to sound attenuation devices (e.g. bubble curtains and pile caps) to reduce the noise level. They refer to the technical and practical limitations to optimize the use of passive acoustic monitoring to augment visual observations. Daley et al. (2012) conclude with a number of suggestions to further develop research/technologies to better support policy decisions including behavioural response data, linking individual responses with population-level effects, acoustic propagation-modelling programmes, improvement of passive acoustic monitoring systems and techniques to assess the effectiveness of current mitigation measures.

There are important differences in the monitoring and mitigation guidelines among parties within the EU. Again, most guidelines have been developed with regard to offshore wind farm construction. The guidelines may be clearly described in nationally accepted documents or may be issued on a project basis. Some guidelines and conditions are described for EIA requirements, and others focus on the construction and operation phases of offshore wind farm developments. Examples of guidelines are in Table 2.

Relevant documents, including national guidelines include: Germany: BSH 2007a, 2007b, 2008; United Kingdom: DEFRA 2005, JNCC 2010a; and The Netherlands: Prins *et al.* 2008.

Table 2. Examples of guidelines for preventing and/or mitigating negative effects on marine mammals in the framework of the construction of offshore wind farms in European waters.

Country	Pile driving requirements			
	Acoustic deterrents	Marine mammal observers	Seasonal restrictions	Soft-start/ ramp-up
Belgium	Yes, taken up in the permit	No	Yes, but only in the advice: no piling 1 Jan to 30 Apr	Yes, taken up in the permit, not standardized
Denmark	Yes	No	Currently none	Yes, but not standardized
Germany	Yes	No	Currently none	Yes
The Netherlands	Yes, general guideline	No	Yes, no piling 1 Jan to 1 July	Yes
United Kingdom	Case by case basis	Before and during, and/or real-time acoustic monitoring	None	Yes

In the US, the use of air bubble curtains is required as a mitigation measure by NMFS during potentially harmful operations in areas where they are likely to be effective.

Camphuysen and Siemensma (2011) recommend in their conservation plan for the harbour porpoise in Dutch waters a precautionary approach to the management and regulation of underwater sound when designing measures to mitigate adverse (disturbance, temporary physical damage) and potential lethal effects of impulsive sound under water. The plan recommends several measures to be applied directly, among which the establishment of guidelines to mitigate the effects of impulsive sounds. It is advised to finalize and fine-tune such guidelines, preferably in cooperation with the regulatory body, that is responsible for the implementation and compliance of the guidelines. Such a set of guidelines should also be adapted whenever new knowledge, developments and insights become available.

Several mitigation measures are proposed in the conservation plan in order to mitigate the adverse effects of pile driving: (1) avoid pile driving and use alternative foundation methods available; (2) have on-board observers when pile driving, and only pile drive in daylight hours and under good sighting conditions; (3) only permit pile driving in seasons of low porpoise abundance to limit the number of animals exposed, based on the latest insights in seasonal distribution; (4) a pre-piling search 30 minutes prior to the start of piling should be undertaken by skilled marine mammal observers. Piling should not begin, if porpoises (or other marine mammals) are detected within the mitigation zone (This zone has to be defined but should be no less than 500 metres based on the UK piling protocol) or until 20 minutes after the last detection; (5) when pile driving, mitigation measures such as acoustic deterrents or a ramp-up procedure should be properly used to alert porpoises and other marine mammals. There is a concern that acoustic deterrents might cause adverse effects as well when to close to the animals. It is not guaranteed that acoustic deterrents or a ramp-up scheme deter porpoises, and if so, animals are disturbed from their natural behaviour; (6) Technical measures proven to reduce the sound emission during construction works should be used whenever possible; (7) the decommissioning phase should avoid underwater explosions, or only be allowed under controlled conditions using bubble curtains or similarly effective mitigation measures to achieve minimum emission of sound into the marine environment.

The conservation plan also advises to establish an appropriate monitoring and policing scheme to ensure compliance to required measures. Protocols for the assessment of the effectiveness of all used mitigation measures should be implemented by the appropriate bodies.

The same plan emphasizes the need for both national and international cooperation, through fora to discuss topics as spatial and temporal planning of acoustic activities at sea and harmonising units and standards.

Apart from direct measures the conservation plan recommends to focus on acoustic monitoring and physical signs of the effects of underwater sound based on necropsied stranded animals.

10. Country specific guidance related to other impulsive underwater noise

A review of the regional marine mammal mitigation guidelines implemented during industrial seismic surveys is provided by Weir and Dolman (2007) as guidance toward a worldwide standard.

Brazil, Canada, New Zealand and **Russia** have introduced regulations for seismic surveys (Minerals Management Service 2004, IBAMA 2005, Department of Conservation 2006). However, these regulations or guidelines differ in terms of the protected species, their approach, focus and required mitigation measures. They conclude that there are three main methods currently used to mitigate the potential impacts on marine mammals during seismic surveys: (1) implementation of operational procedures (*e.g.*, 'soft start'—where sound levels are gradually increased over time); (2) detection of animals close to airguns and implementation of real-time mitigation measures (*e.g.*, shut-down), and (3) time/area planning of surveys to avoid marine mammals. Detection of animals via real-time monitoring, while not a mitigation measure per se, is an essential component of marine mammal mitigation during seismic surveys and is therefore discussed throughout this article in a mitigation context.

Article 7 of the Protocol on Environmental Protection to the Antarctic Treaty Protocol on Environmental Protection to the Antarctic Treaty 1991 bans all mineral resource activities in **Antarctica**, yet despite the sensitivity of the region, research seismic surveys are permitted with only ad hoc marine mammal mitigation in place that depends predominantly on the awareness and interest of the individual operator (see Weir and Dolman 2007).

Some countries have more specific regulations which are listed below:

United Kingdom

The JNCC has revised their guidelines for conducting seismic surveys (JNCC 2010b) which were widely adopted by regulators in several European countries before with regard to managing various anthropogenic sound sources at sea.

JNCC has also written a best practice guidance document for explosive use (JNCC 2010c).

<u>Detailed requirements for construction on wind farms:</u>

- Development license from Crown Estate/DECC.
- FEPA license issued by the Department for Environment, Food and Rural Affairs (Defra); as part of this licensing process Defras seek advice from other bodies: Centre for Environment, Fisheries and Aquaculture Science (Cefas, an Agency of Defra), JNCC, Natural England.

A FEPA license is required for the deposit of any substance or articles in the sea or under the sea bed in UK waters, UK controlled waters or from UK vessels. When making applications for FEPA construction licenses, applicants are required to provide specific details about the project. With regard to the noise emissions a typical FEPA license (Round 2) comprises the following requirements:

> *A) Construction*
>
> *The License Holder must undertake measurements of the noise generated by the installation of foundation pieces. Measurements will need to be taken at various distances for the first few foundation pieces (minimum of four) including during the 'soft start' procedure. The specification for these measurements should be agreed with the Licensing Authority, consultation with Cefas and Natural England at least four months before the construction work commences. The results of these initial measurements should be processed and the report submitted to the Licensing Authority within six weeks of the installation of the first foundation piece. Assessment of this report by the Licensing Authority will determine whether or not any further noise monitoring is required. Should noise levels be significantly in excess of those predicted during the Environmental Impact*

Assessment process then further pile installation will not occur without the consent of the Licensing Authority.

B) Operation

The License Holder must develop plans for subsea noise and vibration from the turbines to be assessed and monitored during the operational phase of the wind farm. Before completion of the construction phase the License Holder must supply specification to the Licensing Authority of how it proposes to measure subsea noise and vibration. These measurements must be taken various frequencies across the sound spectrum at a selection of locations immediately adjacent to, and between turbines, within the array and outside the array at varying distances.

To obtain these licenses developers are required to undertake and Environmental Impact Assessment (EIA) and submit an Environmental Statement (ES) at the planning stage. Noise monitoring as well as mitigation measures to reduce the impact on marine mammals are required during the construction phase. There are, however, no limits regarding the noise emissions during any of the construction or operational activities in UK waters.

<u>Required mitigation:</u>

A soft-start (*i.e.*, the gradual increase of emitted sound energy over a given period of time) is required, but not specified by the regulator. Marine mammal observers are required, as well as passive acoustic monitoring. They must ensure that no marine mammals are detected within a 500 m zone around the piling vessel/ platform for at 30 min prior to the onset of piling. Visual observation must continue throughout the piling. Piling must be stopped if a marine mammal is observed.

A typical underwater sound measurement plan comprises:

- Measure as a function of range to estimate the ‘source level’ along predetermined transects
- Different directions for each pile often measured
- Ideally choose transects with relatively flat bathymetry
- Sometimes toward protected areas, *etc.*
- Place fixed noise monitoring buoys to measure entire piling sequence
- provide a range independent measurement–used for ‘level calibration’
- necessary because of soft-start
- Measure ambient noise in the area–before and/or after
- Log metadata:
    - Water depth at each measurement location
    - CTD measurement in the survey area
    - Wind speed/sea-state
    - GPS position at each measurement location

<u>A detailed case example:</u>

Acoustic measurements as a function of range to estimate the ‘source level’ along predetermined transects can be performed from a vessel or with static buoys. For vessel based measurements the vessel starts as close as possible to the source, and measurements are made at 250, 500, 750, 1000, 1500, 2000, 3000, 5000, 7500 m, *etc.* The vessel must drift silently during the measurements. Generally two hydrophones are deployed on weighted line. The hydrophones lowered to a fixed depth, with one below mid-water column and one close to mid-water column. This arrangement is chosen to avoid surface noise and possible noise from the seabed. The weight must not touch the bottom and must be ~3 m below the lower hydrophone. It is also important to isolate the hydrophones from surface motion of the vessel. Vessel based measurements can be achieved quickly and provide accurate measurements of high intensity sources like pile driving. They are ineffective however for measurements of soft-starts, for observing effects of environmental conditions on noise levels, or for long-term ambient recordings.

Static buoy measurements are made to provide level calibrations and measurements of full sequence of a pile-driving operation from soft-start through completion of all four test piles. Typically two positions are used, at 1.5 and 3.0 km from the pile-driving operation. Measurements are often made at 2.5 and 7.5 m above the sea bed, using a sample rate of at least 96 kS/s.

Visual monitoring and passive acoustic monitoring near pile driving operations have limited value in terms of direct mitigation. Visual observation of marine mammals (especially for small species like the harbour porpoise) usually requires calm weather conditions (sea state ≤ 3) and can be conducted only in daylight with good to moderate visibility (*i.e.*, no fog). However, the monitoring radius is limited to only a few hundred metres for small cetacean species like the harbour porpoise. Moreover, to effectively prevent animals from exposure to excessive sound levels close to the piling operation, the observer must have the authority to stop operations. No such mandate is clearly defined in the regulations. Passive acoustic monitoring with CPODs allows for only offline analysis for the presence and habitat use by odontocetes, *i.e.*, after construction has occurred. As a mitigation tool, active acoustic monitoring devices would have to analyse the data in real-time (via a click detector) and inform the observers or pile driving operators via uplink of the presence of an odontocete.

Ireland

The *Code of Practice for the Protection of Marine Mammals during Acoustic Seafloor Surveys in Irish Waters* (2007) regulates seismic surveys in Irish waters. It is implemented with special reference to the acoustic emissions of this activity and its potential harmful effects on marine mammals. The Code includes numerous mitigation measures which are specific for different techniques used for seismic surveys. The measures comprise among others general planning, pre-start scan for marine mammals (differing with regard to water depth), and soft-start procedures.

Unites States of America

The impact due to underwater explosions is regulated differently from other impulsive sounds. The noise exposure criterion is based on SPL and SEL (i.e. a dual criterion). The criterion for a type of hearing threshold shift (TTS or PTS) to occur is that either or both of thresholds have to be exceeded. The SEL levels are weighted based on the type II weighting function proposed by Finneran and Jenkins (2012). Based on thresholds suggested by Finneran and Jenkins (2012) the thresholds for harbour porpoises as a high frequency cetacean are: onset TTS at a SEL of 146 dB, onset PTS at a SEL 161 dB SEL. The threshold for the zero-to-peak SPL for onset TTS is 195 dB, for onset PTS 201 dB. However, as Ainslie (2012) states, these thresholds have not been applied for non-naval operations.

Australia

The EPBC Act Policy Statement 2.1 (Australian Government, 2008) regulates seismic activities in Australian waters with respect to offshore seismic exploration and its potential effect on whales. It includes requirements specific for this activity such as observer requirements, observation technique and a set of mitigation measures: a source exclusion zone (EZ), soft start/ramp-up including a delay or shut-down for animals within the EZ, pre-shoot watch, special provision for night-time airgun use and the use of passive acoustics. A time/area closure applies only for the Great Australian Bight for southern right whales and Australian fur seals. The radii of the monitoring areas are:

For proposed seismic surveys that can demonstrate through sound modelling or empirical measurements that the received sound exposure level for each shot will not likely exceed 160dB re 1μPa^2·s, for 95% of seismic shots at 1km range, the following precaution zones are recommended:

Observation zone: 3+ km horizontal radius from the acoustic source.

Low power zone: 1 km horizontal radius from the acoustic source.

Shut-down zone: 500m horizontal radius from the acoustic source.

For all other proposed seismic surveys:

Observation zone: 3+ km horizontal radius from the acoustic source.

Low power zone: 2 km horizontal radius from the acoustic source.

Shut-down zone: 500m horizontal radius from the acoustic source.

11. Further Approaches

As a predictive tool for mitigating the impact of underwater sound on marine mammals, the application of spatial modelling is recommended (see Agardy *et al.* 2007) to predict areas of primary importance for marine mammals. Examples of such efforts are:

- OBIS-SEAMAP: Marine mammal data and modelling,
- Modelling global densities and biodiversity hotspots of marine mammal species using a relative environmental suitability model,
- ACCOBAMS collaborative effort to map high density areas for beaked whales in the Mediterranean, and
- PCAD (see paragraph 4.2.9.8)
- PCOD (see paragraph 4.2.9.8)
- EDA PoMM: The "European Defence Agency Protection of Marine Mammals" project is a joint effort of the Ministries of Defence for Germany, Italy, the Netherlands, Norway, Sweden and the United Kingdom. The project aims to protect marine mammals against the impact of active sonar deployed by European Navies by the implementation of robust risk mitigation measures (both in operational planning and at sea). To contribute to this aim, the EDA PoMM project will establish a comprehensive common marine mammal database containing the information needed for risk assessment, planning of naval maritime activities and operational decision aids. The database will focus on the abundance, seasonal distribution and density of marine mammal species in all areas of operational interest for European Navies. In addition aspects of marine mammal acoustics will be data based to aid further work of the project to improve the detection algorithms and classification of marine mammal acoustic signatures.
- SAKAMATA: TNO has developed a software package, SAKAMATA, that supports sonar operators and planners in performing active sonar operations in an environmentally responsible way. It allows the user to check which marine mammals are likely to be in the operating area and how sensitive their hearing is. A database in SAKAMATA also caters for the audiovisual monitoring of marine mammals. The system generates advice for using sonar in each operating area. Part of this advice is a 'ramp-up scheme' (also known as 'soft-start') that takes account of the sonar specifications, the environmental conditions (sound propagation) and the types of marine mammals present in the operating area. Using a ramp-up gives the animals the opportunity to seek a quieter area during a sonar operation. Other options for mitigation, such as changing the operation area, season, duration of the operation or adjusting sailing speeds can also be assessed with SAKAMATA, like changing the operation area or the time of operation. The SAKAMATA system could also serve as a frame of reference when considering mitigation instruments for sound sources other than sonar.

12. Discussion

In this discussion the most important aspects of the current existing regulations (as well as dissimilarities between national regulations) and their applicability to the Dutch situation will be reflected.

The potentially adverse effects of underwater sound on the marine environment in general and marine mammals in particular have become a major topic in the Netherlands as well as in Europe and worldwide. Given the strict protection required under the Flora and Fauna Act for the Harbour Porpoise, and the requirements under the Habitats Directive article 12(1), The Netherlands has the obligation to address activities causing disturbance or killing. For this reason, activities causing impulsive underwater sound should be monitored and regulated, assessing the impact and mitigating the adverse effects (Camphuysen and Siemensma, 2011).

The aim of implementing noise exposure criteria into offshore marine regulations is to prevent negative effects to marine fauna from exposure to intense anthropogenic sounds. This implies that all species at risk should be equally protected from auditory damage if these criteria are to be enforced. The biggest deficit, however, is the current lack of data on auditory sensitivity and tolerance to intense sound in many marine species. Most data on TTS have been measured in only a small number of marine mammal species, and the data indicate substantial differences with regard to hearing sensitivity and vulnerability to TTS between individuals as well as functional hearing groups (species using high-frequency echolocation signals *vs.* species emitting mid-frequency signals). Consequently, any noise exposure criterion may be effective only if it is based on data from the 'most sensitive' species occurring in the area of concern.

The assessment and regulation with respect to offshore pile driving is complicated by the fact that there is no standardized procedure for the measurement and analysis of the acoustic source characteristics of this activity yet. Nevertheless, there are attempts by several countries to reduce the adverse effects of offshore pile driving by establishing guidelines and protocols requiring Environmental Impact Assessments (EIA) and hence mitigation in some cases and/or monitoring of the adverse effects.

The measures taken by different countries to address pile-driving noise vary and no perfect guideline seems to be developed yet. There are some countries which established noise exposure criteria, however these differ in their principal approach. Noise exposure criteria in the US focus on the received sound levels. The US approach requires detailed and reliable information on the abundance and distribution of marine mammals in the vicinity of the pile driving site during the planning phase, and comprehensive information on the occurrence of animals at risk during the activity itself. However, harbour porpoises are difficult to detect visually and acoustically due to the mainly submerged lifestyle and directional echolocation signals. Therefore, the required level of certainty in detecting the presence of these animals during pile driving can't be provided for wider areas or during periods of low visibility (e.g. at night or in bad weather conditions). German regulations on the other hand, include a stand-off distance from the sound source where then noise exposure criterion must be met at its perimeters. This regulation triggers on the one hand operators to reduce the sound level at the source applying quieter construction techniques to meet the noise criterion and on the other hand mitigation measures to reduce the sound propagation and the received level at the receiver side. Again, within the stand-off distance a reliable detection of animals is required and can't always be met.

Modelling of cumulated sound exposure over the duration of a single pile driving event suggests that levels sufficient to elicit PTS could be reached for both seals and porpoises at distances of around 1 km from the piling site (Brandt *et al.* 2011). For this reason mitigation measures in the form of soft-start/ ramp-up procedures and use of acoustic deterrent devices (pingers and seal scarers) immediately before piling have been introduced in order to deter animals out of the impact area before piling commences. However, these modelling based on the exposure criteria of Southall *et al*. (2007) is based on the injury criterion (as a key criterion of the US regulation) and, moreover, did not include information about harbour porpoise as this was not available at that time. When Gordon *et al.* (2010) used the thresholds of Lucke *et al.* (2009) in the model, the 'safe distance' based on harbour porpoise data increased to ~10 km.

Other approaches currently used to mitigate the adverse effect of pile driving are temporal or spatial measures, i.e. to exclude pile driving from specific areas or periods of the year. Dutch regulations e.g. established a temporal closure for pile driving in the first half of the year. Though, as the reproductive season is not covered by this regulation this temporal closure for offshore pile driving is of limited protective value for the harbour porpoise.

Moreover, due to its high mobility and irregular occurrence throughout Dutch waters as well as waters of neighbouring countries an internationally integrated spatial planning and regulation would be most appropriate.

The Dutch regulations are the only ones that consider cumulative impacts from simultaneous construction of wind farms, *i.e.*, pile driving at different sites, within Dutch waters. However, as in most other countries these regulations only apply to the construction of wind farms while all other offshore construction is not regulated in terms of their acoustic emissions. Furthermore, due to a lack of cross-border spatial planning and international regulatory efforts simultaneous construction activities in Dutch waters and neighbouring areas (Germany, Denmark, Belgium, UK) are not yet considered in the Dutch regulations.

Currently several regulations are under review. The German UBA states that its criterion is to be regarded as an interim criterion especially with respect to individual differences and cumulative impacts and that it will be revised as new relevant information becomes available.

Given the uncertainties, lack of data and on-going developments, it is evident that regulators when defining criteria and/or requiring mitigation measures follow and adaptive management strategy in order to strengthen or loosen their regulations based on new knowledge and insight.

13. Quality Assurance

IMARES utilises an ISO 9001:2008 certified quality management system (certificate number: 124296-2012-AQ-NLD-RvA). This certificate is valid until 15 December 2015. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V. Furthermore, the chemical laboratory of the Fish Division has NEN-EN-ISO/IEC 17025:2005 accreditation for test laboratories with number L097. This accreditation is valid until 27 March 2013 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation.

References

Agardy, T., Aguilar, N., Canadas, A., Engel, M., Frantzis, A., Hatch, L., Hoyt, E., Kaschner, K., LaBrecque, E. et al. 2007. A Global Scientific Workshop on Spatio-Temporal Management of Noise Report of the Scientific Workshop. Puerto Calero, Lanzarote, Jun 4-6. 44 p. http://www.okeanos-foundation.org/assets/Uploads/str2007en.pdf

Ainslie, M.A., de Jong, C.A.F., Dol, H.S., Blacquière, G. and Marasini, C. 2009. Assessment of natural and anthropogenic sound sources and acoustic propagation in the North Sea. TNO report TNO-DV 2009 C085. Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (Netherlands Organization for Applied Scientific Research), The Hague.

Ainslie, M.A., de Jong, C.A.F., Robinson, S.P. and Lepper, P.A. 2010. What is the source level of pile driving noise in water? In: 2nd International Conference on the Effects of Sound on Aquatic Life. Cork, Ireland. Pp. 15-20.

Ainslie, M.A. (2012). Current US National Marine Fisheries Service criteria for assessing the effects of underwater sound on marine life. TNO report, 26 pp.

Andrew, R. K., Howe, B. M., and Mercer, J. A. 2002. Ocean ambient sound: comparing the 1960s with the 1990s for a receiver off the California coast," Acoust. Res. Lett. Online 3, 65-70.

ANSI/ASA S3.20. 1995. American National Standard Bioacoustical Terminology. American National Standards Institute, Acoustical Society of America, New York.

Australian Government, Department of Environment, Water, Heritage and the Arts (2008). EPBC Act Policy Statement 2.1 – Interaction between offshore seismic exploration and whales. 14 pp.

Beheerseenheid van het Mathematisch Model van de Nordzee: MUMM, BMM, UGMM, Department VI van het Koninklijk Belgisch Instituut voor Natuurwetenschappen. http://www.mumm.ac.be/NL/Management/Sea-based/windmills_docs.php (last viewed 24-01-2013).

Bolle, L.J., de Jong, C.A.F., Bierman, S., de Haan, D., Huijer, T., Kaptein, D., Lohman, M., Tribuhl, S., van Beek, P., van Damme, C.J.G., van den Berg, F., van der Heul, J., van Keeken, O., Wessels P. and Winter, E. 2011. Effect of piling noise on the survival of fish larvae (pilot study). IMARES report no. CO92/11.

Boyd, I.L., B. Brownell, D.H. Cato, C. Clarke, D. Costa, P. Evans, J. Gedanke, R. Gentry, B. Gisiner, et al. 2008. The effects of anthropogenic sound on marine mammals: a draft research strategy. ESF Marine Board Position Paper 13. European Science Foundation, Marine Board. Oostende, Belgium. ISBN 2-912049-85-7.

Brandt, M. J., Höschle, C., Diederichs, A., Betke, K., Matuschek, R., Witte, S. and Nehls, G. 2012. Effectiveness of sealscarer in deterring harbour porpoises (*Phocoena phocoena*). Final report to Project Management Jülich, 110 p.

Bundesamt für Seeschiffahrt und Hydrographie 2013. http://www.bsh.de/en/Marine_uses/Industry/Wind_farms/index.jsp (last viewed 02-01-2013).

BSH, Bundesamt für Seeschiffahrt und Hydrographie 2007a. Standard - Design of offshore wind turbines. Federal Maritime and Hydrographic Agency (BSH).

BSH, Bundesamt für Seeschiffahrt und Hydrographie 2007b. Standard - Investigations of the Impacts of Offshore Wind Turbines on the Marine Environment. Federal Maritime and Hydrographic Agency (BSH).

BSH, Bundesamt für Seeschiffahrt und Hydrographie 2008. Standard – Ground investigations for offshore wind farms. Federal Maritime and Hydrographic Agency (BSH)

CALTRANS 2001. San Francisco–Oakland Bay Bridge east span seismic safety project, pile installation demonstration project. Marine mammal impact assessment. California Department of Transportation.

Camphuysen C.J. & M.L. Siemensma (2011). Conservation plan for the Harbour Porpoise *Phocoena phocoena* in The Netherlands: towards a favourable conservation status. NIOZ Report 2011-07, Royal Netherlands Institute for Sea Re- search, Texel.

Costa, D.P., Schwarz, L., Schick, R. S., New, L. F., Thomas, L., Hindell, A., McMahon, C., Robinson, P. W. and Simmons, S. E. 2011. A Bioenergetics Approach to Understanding the Population Consequences of Acoustic Disturbance: Elephant seals as a Model System. Presentation at ESOMM-2011 4th Conference on the Effects of Sound in the Ocean on Marine Mammals, Amsterdam., 5-9 Sept. 2011.

Daly, J. N. , Harwood, J., Clark, J.S. and Harrison, J. 2012. The Marine Mammal Protection Act: A Regulatory Approach to Identifying and Minimizing Acoustic-Related Impacts on Marine Mammals, In: A. N. Popper and A. Hawkins (Eds.), The Effects of Noise on Aquatic Life, (Springer, New York), pp. 537-540.

DEFRA. 2005. Nature conservation Guidance on Offshore Windfarm Development: a Guidance Note for Developers Undertaking Offshore Wind farm Developments. Department of Environment, Food and Rural Affairs, UK.

De Jong, C.A.F., Ainslie, M.A. and Blacquière, G. 2011. Standard for measurement and monitoring of underwater noise, Part II: procedures for measuring underwater noise in connection with offshore wind farm licensing. TNO Report TNO-DV 2011 C251. Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (Netherlands Organization for Applied Scientific Research), The Hague. 56 p.

Department of Conservation 2006. Guidelines for Minimising Acoustic Disturbance to Marine Mammals from Seismic Survey Operations. Department of Conservation, Wellington, New Zealand. 10 p. http://www.doc.govt.nz/publications/conservation/native-animals/marine-mammals/minimising-acoustic-disturbance-to-marine-mammals-from-seismic-surveys/.

Elmer, K.-H. 2010. Pile driving noise reduction using new hydro sound dampers. In: Presented at Pile Driving in Offshore Wind Farms: Effects on Harbour Porpoises, Mitigation Measures and Standards. Workshop organised by the Federal Maritime and Hydrographic Agency (BSH), Stralsund, Germany, Mar 21.

Erbe, C., and King, A.R. 2009. Modeling cumulative sound exposure around marine seismic surveys. J. Acoust. Soc. Am. 125(4):2443-2451.

Fernández, A., J.F. Edwards, F. Rodriguez, A.E. de los Monteros, P. Herraez, P. Castro, J.R. Jaber, V. Martin, and M. Arbelo. 2005. "Gas and fat embolic syndrome" involving a mass stranding of beaked whales (Family *Ziphiidae*) exposed to anthropogenic sonar signals. Vet. Pathol. 42(4):446-457.

Finneran, J. J., C.E. Schlundt, D.A. Carder, J.A. Clark, J.A. Young, J.B. Gaspin and S.H. Ridgway. 2000. Auditory and behavioral responses of bottlenose dolphins (*Tursiops truncatus*) and white whales (*Delphinapterus leucas*) to impulsive sounds resembling distant signatures of underwater explosions. J. Acoust. Soc. Am. 108: 417–431.

Finneran, J.J., C.E. Schlundt, R. Dear, D.A. Carder, and S.H. Ridgway. 2002. Temporary shift in masked hearing thresholds in odontocetes after exposure to single underwater impulses from a seismic watergun. J. Acoust. Soc. Am. 111(6): 2929-2940.

Finneran, J.J., D.A. Carder, C.E. Schlundt, and S.H. Ridgway. 2005. Temporary threshold shift in bottlenose dolphins (*Tursiops truncatus*) exposed to mid-frequency tones. J. Acoust. Soc. Am. 119(4): 2696-2705.

Finneran, J.J., C.E. Schlundt, B. Branstetter, and R.L. Dear. 2007. Assessing temporary threshold shift in a bottlenose dolphin (*Tursiops truncatus*) using multiple simultaneous auditory evoked potentials. J. Acoust. Soc. Am. 122(2): 1249-1264.

Finneran, J. J. and Schlundt, C. E. 2009. Auditory weighting functions and frequency dependent effects of sound in bottlenose dolphins (*Tursiops truncatus*), In: 2009 ONR Marine Mammal Program Review (Alexandria, VA).

Finneran, J.J., D.A. Carder, C.E. Schlundt, and R.L. Dear. 2010. Growth and recovery of temporary threshold shift at 3 kHz in bottlenose dolphins: Experimental data and mathematical modelsa. J.

Acoust. Soc. Am. 127(5): 3256-3266.

Finneran, J. J. and Schlundt, C. E. 2011. Subjective loudness level measurements and equal loudness contours in a bottlenose dolphin (*Tursiops truncatus*), J. Acoust. Soc. Am. 130, 3124-3136.

Finneran, J.J. and Jenkins, A.K. 2012. Criteria and Thresholds for U.S. Navy Acoustic and Explosive Effects Analysis. SSC Pacific, 64 pp.

Frantzis, A. 1998. Does acoustic testing strand whales? Nature 392(6671):29.

Frisk, G.V. (2007). Noiseonomics: The relationship between ambient noise levels and global economic trends. Frisk, G.V. 2007. Paper presented at Pacific Rim Underwater Acoustics Conference 2007, Vancouver, BC, Canada, October 3–5, 2007 (http://pruac.apl.washington.edu/abstracts/frisk.pdf).Gilliland, P.M., and Laffoley, D. 2008. Key elements and steps in the process of developing eco-system-based marine spatial planning. Marine Policy 32(5):787–796.

Gordon, J. 2010. Potential effects on marine mammals. Presentation at "Assessing and managing the potential impact of marine piling noise within the evolving regulatory framework", Underwater Sound Forum, February 24th, 2010, London.

Gunderboom. 2011: online: http://www.gunderboom.com/sas/sas_2.html

Hatch, L. T., and Wrigth, A. J. 2008. A Brief Review of Anthropogenic Sound in the Oceans, Int. J. Comp. Psychol. 20: 121-133.

Heitmeyer, R. M., Wales, S. C., and Pflug, L. A. 2004. Shipping noise predictions: capabilities and limitations, Mar. Tech. Soc. J. 37: 54-65.

Hildebrand, J. 2004. Impacts of anthropogenic sound on cetaceans, (SC/56/E13) International Whaling Commission, Cambridge, UK.

IBAMA 2005. Brazilian Environmental Licensing Guide. Atividades de Sísmica Marítima na Costa Brasileira. Brazilian Institute of Environment and Natural Resources (Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis). http://www.anp.gov.br/ibamasismica (Accessed May 2006).

ICES Working Group on Marine Mammal Ecology (WGMME). 2010. Report of the Group on Marine Mammal Ecology. April 12–15 2010, Horta, The Azores, Portugal. ICES CM 2010/ACOM:24: 212 pp.

ICES Working Group on Marine Mammal Ecology (WGMME). 2011. Report of the Working Group on Marine Mammal Ecology (WGMME), 21–24 February 2011, Berlin, Germany. ICES CM 2011/ACOM:25: 204 pp.

ICES Working Group on Marine Mammal Ecology (WGMME). 2012. Report of the Working Group on Marine Mammal Ecology (WGMME), 5–8 March 2012, Copenhagen, Denmark. ICES CM 2012/ACOM:27: 146 pp.

ISD, Institut für Statik und Dynamik 2010: Vergleich verschiedener Blasenschleierkonzepte und Darstellung des Forschungsbedarfs (in German).

Jacobs, D.W., and Hall, J.D. 1972. Auditory thresholds of a fresh water dolphin, *Inia geoffrensis* Blainville. J. Acoust. Soc. Am. 51(2): 530-533.

JNCC, Joint Nature Conservation Committee 2009. Statutory nature conservation agency protocol for minimising the risk of disturbance and injury to marine mammals from piling noise. Joint Nature Conservation Committee, Aberdeen.

JNCC, Joint Nature Conservation Committee 2010a. Statutory nature conservation agency protocol for minimising the risk of injury to marine mammals from piling noise. Joint Nature Conservation Committee, Aberdeen, UK. 14 p.

JNCC, Joint Nature Conservation Committee 2010b. JNCC guidelines for minimising the risk of injury and disturbance to marine mammals from seismic surveys. Joint Nature Conservation Committee, Aberdeen, UK. 16 p. http://jncc.defra.gov.uk/pdf/jncc_guidelines_seismic%20guidelines_aug%202010.pdf

JNCC, Joint Nature Conservation Committee 2010c. Guidelines for minimising the risk of injury to marine mammals from using explosives. Joint Nature Conservation Committee, Aberdeen.

Kastak, D., Southall, B. L., Schusterman, R. J., and Reichmuth Kastak, C. 2005. Underwater temporary threshold shift in pinnipeds: Effects of noise level and duration, J. Acoust. Soc. Am. 118: 3154-3163.

Kastak, D., Mulsow, J., Ghoul, A., and Reichmuth, C. 2008. Noise-induced permanent threshold shift in a harbor seal, J. Acoust. Soc. Am. 123 (5/2): 2986.

Kastelein, R.A., Hoek, L., Jennings, N., de Jong, C.A.F., Terhune, J.M. and Dieleman, M. 2010 Acoustic mitigation devices (AMDs) to deter marine mammals from pile driving areas at sea: Audibility & behavioural response of a harbour porpoise & harbour seals. COWRIE Ref: SEAMAMD-09, Technical Report – Executive summary, 7 p.

Kastelein, R.A., Gransier, R., Hoek, L. and de Jong, C.A.F. 2012a. The hearing threshold of a harbor porpoise (*Phocoena phocoena*) for impulsive sounds (L). J. Acoust. Soc. Am. Volume 132(2): 607-610.

Kastelein, R.A., Gransier, R., Hoek, L. and Olthuis, J. 2012b. Temporary threshold shifts and recovery in a harbour porpoise (*Phocoena phocoena*) after octave-band noise at 4 kHz. J. Acoust. Soc. Am. Volume 132(5): 3525-3537.

Ketten, D.R. 2006. Experimental measures of blast and acoustic trauma in marine mammals. ONR final report N000149711030.

Koschinski, S. and Lüdemann, K. 2011. Stand der Entwicklung schallminimierender Maßnahmen beim Bau von Offshore_Windenergieanlagen. Studie im Auftrag des Bundesamt für Naturschutz, 88 p. (in German).

Kryter, K.D. 1994. The handbook of hearing and the effects of noise: Physiology, psychology, and public health. In. Academic Press, New York.

Lee, K.M., Wochner, M.S. and Wilson, P.S. 2012. Mitigation of low-frequency underwater anthropogenic noise using stationary encapsulated gas bubbles. Presentation at ECUA 2012, 11thEuropean Conference on underwater Acoustics, Edinburgh, 2-6 July 2012.

Le Prell, C. 2010. Noise-induced hearing loss: from animal models to human trials. In: Presentation at the 2nd international conference on "The Effects of Noise on Aquatic Life". Cork, Ireland, August 15-20.

Lucke, K., Siebert, U., Lepper, P.A. and Blanchet, M.-A. 2009. Temporary shift in masked hearing thresholds in a harbor porpoise (*Phocoena phocoena*) after exposure to seismic airgun stimuli. J. Acoust. Soc. Am. 125(6): 4060-4070.

Lucke, K., Lepper, P.A. Blanchet, M.-A. and Siebert, U. 2011. The use of an air bubble curtain to reduce the received sound levels for harbor porpoises (*Phocoena phocoena*). J. Acoust. Soc. Am. 130(5): 3406-3412.

Lusseau, D., Christiansen, F., Harwood, J., Mendes, S., Thompson, P. M., Smith, K., Hastie, G.D. 2012. Assessing the risks to marine mammal populations form renewable energy devices – an interim approach. Final Workshop report, 29 pp.

McDonald, M. A., Hildebrand, J. A., and Wiggins, S. M. 2006. Increases in deep ocean ambient noise in the Northeast Pacific west of San Nicolas Island, California, J. Acoust. Soc. Am. 120(2): 711-718.

Miller, P.J.O., Kvadsheim, P.H., Lam., F.-P.A., Wensveen, P.J., Antunes, R., Alves, A.C., Viser, F., Kleivane, L., Tyack, P.L., Doksæter Sivle, L. 2012. The severity of behavioral changes observed during experimental exposure of killer (*Orcinaus orca*), long-finned pilot (*Globicephala melas*), and sperm (*Physeter macrocephalus*) whales to naval sonar. Aq. Mamm., 38(4): 362-401.

Minerals Management Service 2004. Implementation of Seismic Survey Mitigation Measures and Protected Species Observer Program. NTL No. 2007-G02 Effective Date: February 7, 2007. Notice to lessees and operators (ntl.) of Federal oil, gas, and sulphur leases in the outer continental shelf, Gulf of Mexico,OCS region. United States Department of the Interior, Minareal Management Service, Gulf of Mexico (GOM) OCS Region

http://www.gomr.boemre.gov/homepg/regulate/regs/ntls/2007NTLs/07-g02.pdf
Müller, A., and Zerbs, C. 2011. Offshore wind farms. Measurement instruction for waterborne sound measurements. Current approach with annotations Basis for discussion (version 2011-06-06). Müller-BBM (draft) report No. M88 607/5. Hamburg.
Nachtigall, P.E., Pawloski, J.L. and Au, W.W.L. 2003. Temporary threshold shifts and recovery following noise exposure in the Atlantic bottlenosed dolphin (*Tursiops truncatus*). J. Acoust. Soc. Am. 113(6):3425-3429.
Nachtigall, P.E., Supin, A.Y., Pawloski, J. and Au, W.W.L. 2004. Temporary threshold shifts after noise exposure in the bottlenose dolphin (*Tursiops truncatus*) measured using evoked auditory potentials. Marine Mammal Science 20: 673-687.
NMFS, National Marine Fisheries Service 2000. Environmental Assessment on the Effects of Controlled Exposure of Sound on the Behaviour of Various Species of Marine Mammals. National Marine Fisheries Service, Silver Spring, MD.
NMFS, National Marine Fisheries Service 2008. Small Takes of Marine Mammals Incidental to Specified Activities; Port of Anchorage Marine Terminal Redevelopment Project, Anchorage, Alaska. In: Federal Register. 73. National Marine Fisheries Service. Document 139 p.
Nowacek, D.P., Thorne, L.H., Johnston, D.W. and Tyack, P.L. 2007. Responses of cetaceans to anthropogenic noise, Mammal Review, 37(2): 81-115.
NRC, National Research Council 1994. Low-Frequency Sound and Marine Mammals: Current Knowledge and Research Needs. National Academy Press, Washington, DC.
NRC, National Research Council 2005. Marine Mammal Populations and Ocean Noise: Determining when noise causes biologically significant effects. In. National Academies Press, Washington.
Nehls, G., Betke, K., Eckelmann, S. and Ros. M. 2007. Assessment and costs of potential engineering solutions for the mitigation of the impacts of underwater noise arising from the construction of offshore windfarms. BioConsult SH report, Germany. On behalf of COWRIE Ltd.
NIOSH 1998. Criteria for a recommended standard: Occupational noise exposure. National Institute for Occupational Safety and Health, U.S. Department of Health and Human Services, Centers for Disease Control and Prevention.
NOAA and U.S. Navy 2001: Joint interim report Bahamas marine mammals stranding event of 15-16 March 2000. – U.S. Department of Commerce, NOAA, NMFS, US-Navy. www.nmfs.noaa.gov/pr/pdfs/health/stranding_bahamas2000.pdf - 2006-05-09 (last visited 26-11-2011)
OffshoreMarine, 2010. Newsletter September-October 2010, p.30-31, Keppel Offshore & Marine Ltd., Singapore.
OSPAR Commission 200). Quality status report 2000, region II – greater North Sea, OSPAR Commission, London.
OSPAR Commission 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. OSPAR Report 441. Boidiversity Series. OSPAR Commission, London. 133 p.
Pavan, G. 2006. Guidelines to address the issue of the impact of anthropogenic noise on marine mammals in the ACCOBAMS area. In: Report to the 3rd meeting of the ACCOBAMS Scientific Committee. Document Revision 2.1. Monaco.
Popov, V.V., A.Y. Supin, D. Wang, K. Wang, L. Dong, and S. Wang. 2011. Noise-induced temporary threshold shift and recovery in Yangtze finless porpoises *Neophocaena phocaenoides asiaeorientalis*. J. Acoust. Soc. Am. 130(1): 574-584.
Prins, T.C., F. Twisk, V.d. Heuvel, M.J. Greve, T.A. Troost, and J.K.L. Van Beek. 2008. Development of a framework for Appropriate Assessments of Dutch offshore wind farms. In: IMARES report Z4513.
Richardson, W.J., Greene, C.R. , Malme, C.I. and Thomson, D.H. 1995. Marine Mammals and Noise. In. Academic Press, San Diego, CA.
Ridgway, S., and Carder, D. 1997. Hearing deficits measured in some *Tursiops truncatus*, and discovery of a deaf/mute dolphin. J. Acoust. Soc. Am. 101(1): 590-594.

Ross, D. (2005). Ship sources of ambient noise, IEEE J. Ocean. Engineer. 30: 257–261.

Saleem, Z. 2011. Alternatives and modifications of Monopile foundation or its installation technique for noise mitigation. Report commissioned by the North Sea Foundation, 68 pp.

Schlundt, C. E., Finneran, J. J., Carder, D. A., and Ridgway, S. H. 2000. Temporary shift in masked hearing thresholds of bottlenose dolphins, *Tursiops truncatus*, and white whales, *Delphinapterus leucas*, after exposure to intense tones, J. Acoust. Soc. Am. 107 (6), 3496-3508.

Schlundt, C.E., Dear, R.L., Carder, D.A. and Finneran, J.J. 2006. Growth and recovery of temporary threshold shifts in a dolphin exposed to midfrequency tones with durations up to 128 s. J. Acoust. Soc. Am. 120: 3227.

Simmonds, M.P., and Lopez-Jurado, L.F. 1991. Whales and the military. Nature 351:448.

Spence J., R.Fischer, M.Bahtiarian, L.Boroditsky, N. Jones & R. Dempsey 2007. Review of Existing and Future Potential Treatments for Reducing Underwater Sound from Oil and Gas Industry Activities. Prepared for: Joint Industry Programme on E&P Sound and Marine Life, by Noise Control Engineering, Inc., Billerica, MA.

Southall, B. L., Bowles, A. E., Ellison, W. T., Finneran, J. J., Gentry, R. L., Greene, C. R., Jr., Kastak, D., Ketten, D. R., Miller, J. H., Nachtigall, P. E., Richardson, W. J., Thomas, J. A., and Tyack, P. L. 2007. Marine mammal noise exposure criteria: initial scientific recommendations, Aq. Mamm. 33: 411-521.

Tasker M.L., Amundin M., Andre M., Hawkins A., Lang B., Merck T., Sholik-Scholmer A., Teilmann J., Thomsen F., Werner S., Zakharia M. 2010. Indicator for the good environmental status for underwater noise and other form of energy. The main report of task group 11 for Marine Strategy Framework Directive's descriptor 11 Draft 11:01/2010. 39pp ICES/JRC report.

Umweltbundesamt. 2011. Empfehlung von Lärmschutzwerten bei der Errichtung von Offshore-Windenergieanlagen (OWEA). German Federal Environment Agency (Umweltbundesamt). http://www.umweltbundesamt.de/uba-info-medien/4118.html.

Van der Graaf, A.J., Ainslie, M.A., André, M., Brensing, K., Dalen, J., Dekeling, R.P.A., Robinson, S., Tasker, M.L., Thomsen, F., Werner, S. 2012. European Marine Strategy Framework Directive - Good Environmental Status (MSFD GES): Report of the Technical Subgroup on Underwater noise and other forms of energy.

Verfuß, T. 2012. Noise Mitigation Measures & Low-noise Foundation Concepts – State of the Art. Presentation at BfN-Symposium Towards an Env. Sound Offshore Wind Energy Deployment, Stralsund, Germany, 25 Jan. 2012.

Weir, C. R., and Dolman, S. J. 2007. Comparative review of the regional marine mammal mitigation guidelines implemented during industrial seismic surveys, and guidance towards a worldwide standard, J. Intern. Wildlife Law Policy 10: 1-27.

Würsig, B., Greene, C. R. Jr. and Jefferson, T. A. 2000. Development of an air bubble curtain to reduce underwater noise of percussive piling, Mar. Env. Res. 49: 79-93.

Zampolli, M., de Jong, C.A.F., Ainslie, M.A., Jansen, H.W.J., Fillinger, L., Middeldorp, F.M., Hazelwood, R.A., Robinson, S.P. and Jung B. 2011. Pile driving noise: Source level and sound generating mechanisms. In: 161st Meeting of the Acoustical Society of America, Seattle, WA.

Justification

Rapport C044.13
Project Number: 430.8601.034

The scientific quality of this report has been peer reviewed by the a colleague scientist and the head of the department of IMARES.

Approved: Dr.ir. H.V. Winter
Researcher

Signature:

Date: 13th March 2013

Approved: Drs. J. Asjes
Department Head Ecosystems

Signature:

Date: 13th March 2013

14. Appendix A. Acronyms and abbreviations

ADD	acoustic deterrent device
AEP	auditory evoked potential
ASSR	auditory steady state response
dB	decibel
dB re 1 μPa	decibels referenced to 1 microPascal
dB re 1 $\mu Pa^2 s$	decibels referenced to 1 microPascal- squared- seconds
EQL	equal loudness
Hz	hertz
kHz	kilohertz
rms	root-mean-square
PTS	permanent threshold shift
SEL	sound exposure level
SPL	sound pressure level
TTS	temporary threshold shift