

Use of acoustic methods for the
protection of harbour porpoises
(*Phocoena phocoena*) in German Waters



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Summary

Harbour porpoises *Phocoena phocoena* in German waters are faced with a variety of different anthropogenic and natural stressors that can have serious effects on population development. Anthropogenic stressors include prey depletion, influences of chemical and pharmaceutical toxins, by-catch in static fishing gear, noise pollution and habitat degradation. Climate influences add to these stressors and may pose both natural as well as anthropogenic threats. Pile-driving noise for construction of offshore wind farms is a new influence that is suspected to have adverse effects on porpoises.

Within German waters three subpopulations of porpoises can be found. The North Sea subpopulation extends into the Skagerrak and parts of the Kattegat, the Belt Sea subpopulations reaches from these regions into the waters of the Kiel and Mecklenburg Bight while the Baltic Proper subpopulation has its presumed boundaries at the Darß and Limhamn Sills and populates the waters of the inner Baltic Sea. While the abundance of porpoises in the North Sea seems stable, this has been questioned for the Belt Sea subpopulation. The Baltic Proper subpopulation is recognized as ‘critically endangered’ by the IUCN (International Union for Conservation of Nature) red list and surveys within the last decades have not lead to conclusive abundance estimates due to the scarcity of sightings.

Within this study Stationary Acoustic Monitoring (SAM) with echolocation click loggers (T-PODs – Timing Porpoise Detectors and C-PODs – Cetacean PODs, both Chelonia Ltd., UK) was used to describe distribution patterns of porpoises and analyse factors driving acoustic presence of porpoises in German waters. Harbour porpoises use echolocation almost constantly and hence registrations on the loggers represent a relative measure for porpoise presence in an area. This relatively new method is still developing rapidly and neither analysis strategies nor devices are standardized as has been done for other assessment methods. However, when using these devices for monitoring, effect monitoring and other long-term studies, it is essential to standardize the instruments, as well as to develop standard procedures for data evaluation.

To account for variability of the loggers, a rigorous calibration of the instruments was conducted prior to field trials and repeatedly over time. The results indicate that the older T-PODs (Chelonia Ltd., UK) had a wide variation in detection thresholds at the beginning of the study, but newer versions were found to be well standardized. For C-PODs (Chelonia Ltd., UK), the digital successor of the T-POD, the calibration showed a much better standardization at the preferred porpoise vocalisation frequency of 130 kHz. Other frequencies were less comparable indicating that surveys for species using lower frequencies must obtain calibration data for their instruments.

The first long-term deployment of up to 42 T-PODs in the German Baltic Sea documented strong geographical and seasonal differences in porpoise occurrence. Instruments deployed closer together gathered more comparable data than devices further away. This indicates that these differences represent a genuine occurrence pattern with higher detection rates in westerly waters, which gradually decrease towards the Pomeranian Bay in the east. Overall, more porpoises were registered from spring to fall, indicating a possible relationship to herring as one preferred prey item.

A second long-term study was conducted to analyse the echolocation behaviour of porpoises east of the Darß and south of the Limhamn Sill. Detection rates showed two peaks in seasonal occurrence of porpoises at these sites. This result indicates most likely that porpoises from both subpopulations in German waters use the area of the Pomeranian Bay in an alternating pattern of habitat use: porpoises from the Belt Sea distribute throughout German waters from spring to fall, with maximum detection rates in summer, while Baltic Proper porpoises use the area during winter to avoid suffocation in the closed ice cover in the inner Baltic waters. The modelling indicated that salinity was a significant factor for presumed Belt Sea animals, while temperature had significant influences on all detection rates.

To estimate the impact of pile-driving noise on porpoises a third long-term study was conducted off the German coast close to Borkum Reefground, where the first German offshore wind farm *alpha ventus* was constructed from 2008 to 2009. Visual observations showed a strong displacement of porpoises during pile-driving out to a distance of ~20 km around the pile-driving site during a survey exactly timed to the piling activities. Acoustic monitoring showed reduced detection rates close to the pile-driving operation in distances up to 11 km. There were no stations between 11 and 23 km distance. At 25 and 50 km distance detection rates increased indicating that porpoises were possibly displaced towards these positions and hence a behavioural reaction was recorded outside of the displacement radius. Furthermore, the duration of porpoise absence during and after pile-driving was correlated with the duration of pile-driving. From this data it remained unclear whether the displacement process was fully completed.

To mitigate effects, such as described for the construction of *alpha ventus*, more work is necessary to find suitable noise mitigation measures. In a previous project it was shown that a stacked bubble curtain greatly reduced the sound levels, as well as the behavioural reaction in captive porpoises during harbour construction work in Denmark. In a follow up project it was tested which factors actually led to the large attenuation and how different nozzle layouts in a test tank environment under controlled conditions lead to changed attenuation rates. A second test of a single system was carried out in Kiel harbour. For both of these trials an underwater loudspeaker served as the sound source and modulated sine wave impulses were used to test attenuation efficacy. The resulting attenuation rates were much larger than previously reported. This is most probably linked to the sound source that was used in these experiments, which does not behave like a pile being driven. The pile is a line source with contact to three media: air, water and sediment. We tested only the water transmission path in these experiments. However, transmission through the sediment may play a large role in offshore conditions and must be accounted for within future offshore construction work.

Zusammenfassung

Schweinswale *Phocoena phocoena* in deutschen Gewässern sind verschiedenen anthropogenen und natürlichen Stressoren ausgesetzt, die erhebliche Auswirkungen auf die Populationsentwicklung haben können. Dazu gehören vermindertes Beutevorkommen, Einflüsse von chemischen und pharmazeutischen Toxinen, Beifang in stationären Netzen der Fischerei, Schalleinflüsse und Habitatveränderungen. Weiterhin kommen klimatische Einflüsse hinzu, die sowohl als natürliche als auch als anthropogene Gefährdungen betrachtet werden können. Ein neuer potentiell schädlicher Einfluss für Schweinswale sind Rammgeräusche während der Errichtung von Fundamenten für Offshore-Windparks.

In den deutschen Gewässern kommen drei Subpopulationen von Schweinswalen vor. Die Nordsee-Subpopulation kommt ebenfalls in den Gewässern des Skagerraks und zum Teil im Kattegat vor. Die Beltsee-Subpopulation erstreckt sich von dort bis in die Gewässer der Kieler und Mecklenburger Bucht. Die innere Ostsee-Subpopulation hat vermutlich ihre Verbreitungsgrenze an der Darßer und Limhamn-Schwelle und bevölkert die innere Ostsee. Während die Abundanz von Schweinswalen in der Nordsee stabil erscheint, ist dies für die Beltsee-Subpopulation fraglich. Die Subpopulation der inneren Ostsee wird durch die rote Liste der IUCN (International Union for Conservation of Nature) als ‚vom Aussterben bedroht‘ eingestuft. Erfassungen in den letzten Jahrzehnten haben nicht zu belastbaren Bestandszahlen geführt.

In dieser Studie wurde Stationäres Akustisches Monitoring (SAM) mit Echoortungsklickloggern (T-PODs – Timing PORpoise Detectors und C-PODs – Cetaceen PODs, beide Chelonia Ltd., UK) eingesetzt, um Aufenthaltsmuster von Schweinswalen zu analysieren und Faktoren zu ermitteln, die die akustische Präsenz von Schweinswalen in deutschen Gewässern beeinflussen. Schweinswale nutzen Echoortung fortwährend und somit entsprechen die Registrierungsdaten der Logger (akustische Präsenz) einem relativen Maß für die Anwesenheit von Schweinswalen in diesem Areal. Die relativ neue Methode entwickelt sich derzeit schnell weiter, wobei weder die genutzten Maßeinheiten, noch die Geräte einer generellen Standardisierung unterliegen, wie es für andere Erfassungsmethoden üblich ist. Eine Standardisierung der Geräte und der Auswertungsmethoden zu entwickeln ist unerlässlich, um die Geräte für ein Monitoring, Effektmonitoring oder für andere Langzeitstudien einzusetzen.

Eine Kalibrierung der Messgeräte wurde vor den Feldversuchen und in regelmäßigen Abständen wiederholt, um individuelle Unterschiede der Logger zu berücksichtigen. Die Ergebnisse zeigen, dass ältere T-PODs eine große Variation in der Detektionsschwelle zu Beginn der Erfassungen aufwiesen, während neuere Versionen gut standardisiert waren. Für C-PODs zeigte die Kalibrierung eine wesentlich bessere Standardisierung für das von Schweinswalen genutzte Frequenzband um 130 kHz. Andere Frequenzen zeigten weniger vergleichbare Ergebnisse. Dies hat zur Folge, dass für Erfassungen von anderen Walarten mit einer geringeren Vokalisationsfrequenz die Geräte separat kalibriert werden müssen.

Starke saisonale und geografische Unterschiede konnten durch die erste Langzeiterfassung in der deutschen Ostsee mit 42 T-PODs gezeigt werden. Geräte mit einem geringeren geografischen Abstand nahmen dabei ähnlichere Daten auf, als solche mit

größeren Abständen. Die aufgezeichneten Unterschiede der akustischen Daten spiegeln somit höchstwahrscheinlich korrekte Aufenthaltsmuster wieder. In westlichen Bereichen der deutschen Ostsee wurden höheren Registrierungsraten abnehmend zur Pommerschen Bucht im Osten festgestellt. Es wurden vermehrt Schweinswale im Zeitraum von Frühling bis Herbst registriert. Dies könnte im Zusammenhang mit dem Vorkommen von Hering, einer bevorzugten Beutearart, stehen.

Eine zweite Langzeitstudie wurde durchgeführt, um das Echoortungsverhalten von Schweinswalen östlich der Darßer und südlich der Limhamn-Schwelle zu analysieren. Die Ergebnisse zeigen zwei saisonale Maxima der Schweinswalregistrierungsdaten. Schweinswale beider Subpopulationen könnten somit die Gewässer der Pommerschen Bucht alternierend nutzen: Schweinswale der Beltsee-Subpopulation breiten sich von Frühling bis Herbst in deutschen Gewässern aus, mit maximalen Detektionsraten im Sommer, während die innere Ostsee-Subpopulation diese Bereiche im Winter nutzt, um der Erstickungsgefahr unter einer geschlossenen Eisdecke in der inneren Ostsee zu entgehen. Die Modellierung zeigt weiterhin, dass Salinität ein wichtiger Faktor für die Registrierungsdaten von Schweinswalen in der Beltsee ist, während Temperatur einen hohen Einfluss auf die Registrierungsdaten aller Stationen hatte.

Um den Einfluss von Rammgeräuschen auf Schweinswale zu ermitteln wurde eine dritte Langzeitstudie vor der deutschen Küste nahe Borkum Riffgrund durchgeführt, wo der erste deutsche Windpark *alpha ventus* von 2008 bis 2009 errichtet wurde. Visuelle Beobachtungen zeigen eine starke Fluchtreaktion der Schweinswale während der Rammarbeiten in ca. ~20 km Radius um die Baustelle während eines Surveys auf, der exakt zeitgleich mit den Rammarbeiten absolviert wurde. Das akustische Monitoring zeigte reduzierte Registrierungsdaten bis in 11 km Distanz. In den Entfernungen zwischen 11 und 23 km waren keine Messinstrumente ausgebracht. In 25 und 50 km Entfernung waren die Detektionsraten erhöht. Dies deutet darauf hin, dass Schweinswale zu diesen Stationen vertrieben wurden. Dementsprechend konnte eine Verhaltensreaktion von Schweinswalen in einem wesentlich größeren Bereich nachgewiesen werden, als der Vertreibungsradius indiziert. Außerdem war die Länge der Abwesenheit von Schweinswalen während und nach der Rammung mit der Dauer der Rammarbeiten korreliert. Aus den aufgezeichneten Daten ist nicht ersichtlich, ob der Vertreibungsvorgang vollständig abgeschlossen war.

Um die bei *alpha ventus* nachgewiesenen Effekte abzumildern ist weitere Forschung notwendig, um geeignete Schallminderungsmethoden zu finden. In einem Vorgängerprojekt wurde gezeigt, dass ein gestufter Luftblasenschleier die Schallpegel, aber auch die Verhaltensreaktionen von Schweinswalen in Gefangenschaft während Hafenbauarbeiten in Dänemark stark reduzierte. Im hier vorgestellten Folgeprojekt wurde getestet, welche Faktoren zu dieser starken Reduktion der Lautstärke von Rammarbeiten geführt haben und wie verschiedene Luftdüsenlayouts sich in einem Laborversuch unter kontrollierten Bedingungen auf die Effektivität der Abschwächung auswirken. Ein Feldversuch eines Einzelsystems wurde im Kieler Hafen durchgeführt. Für beide Tests wurden Unterwasserlautsprecher als Schallquelle genutzt, die modulierte Sinussignale bei definierten Testfrequenzen aussandten. Die innerhalb der Tests gemessene Abschwächung war wesentlich größer, als bisher berichtet wurde. Dies ist höchstwahrscheinlich durch den Lautsprecher als verwendete Schallquelle zu erklären, der sich akustisch nicht wie ein

gerammter Pfahl verhält. Der Pfahl ist eine Linienquelle, die im Kontakt mit drei verschiedenen Medien steht: Luft, Wasser und Sediment. Von diesen drei Pfaden wurde somit innerhalb der Experimente nur die Wasserschallausbreitung getestet. Dementsprechend könnte die Schallausbreitung durch das Sediment eine größere Rolle unter realen Offshore-Bedingungen spielen und muss für zukünftige Bauvorhaben mit betrachtet werden.

General introduction

Harbour porpoises *Phocoena phocoena* are one of three reproducing marine mammal species in German Waters besides harbour seals *Phoca vitulina* and grey seals *Halichoerus grypus* (Siebert et al., 2012). Of these three species porpoises are the sole representative of cetaceans in Germany and are thus of special importance for conservation efforts under various conservation treaties and commitments. Porpoises are legally protected by Annex II and IV of the European Union's habitats directive (EU, 1992) as well as by international treaties like the Convention on the Conservation of European Wildlife and Natural Habitats (Bern convention, 1979) and the Convention on the Conservation of Migratory Species of Wild Animals (Bonn convention, 1979). Species listed in Annex II of the habitats directive require the designation of Special Areas of Conservation (SACs) while species listed in Annex IV are of community interest in need of strict protection (EU, 1992). Article 12 of the habitats directive specifies that all species listed in annex IV are to be protected "in their natural range" and prohibits "all forms of deliberate capture", "deliberate disturbance [...] particularly during the period of breeding, rearing, hibernation and migration" as well as the "deterioration or destruction of breeding sites or resting places". Further, it is mentioned that "Member States shall [...] ensure that incidental capture and killing does not have a significant negative impact on the species concerned."

Harbour porpoises in German waters are faced with different anthropogenic and natural stressors that may have serious effects on population development. Anthropogenic stressors include prey depletion, influences of chemical and pharmaceutical toxins, by-catch in static fishing gear, noise pollution and habitat degradation (reviewed in Siebert et al., 2012). Climate influences add to these stressors and may pose both natural, as well as anthropogenic threats. Especially the incidental capture in fishing gear (Berggren et al., 2002; Herr, 2009; Scheidat et al., 2008) and influences of construction activity for offshore wind farms are suspected to have negative impacts on porpoises (e.g. Teilmann and Carstensen, 2012). The latter are one focus of this thesis.

Natural history of harbour porpoise (*Phocoena phocoena* Linnaeus 1758)

Harbour porpoises are part of the order Cetacea (whales and dolphins), suborder Odontoceti (toothed whales), superfamily Delphinoidea and family *Phocoenidae*. They are one of the smallest marine mammals occurring in coastal waters of temperate and boreal regions (Bjørge and Tolley, 2009). Harbour porpoise are opportunistic feeders preying mostly on small to medium sized demersal and benthic as well as schooling pelagic fish species (Benke et al., 1998; Gilles et al., 2009a; Santos and Pierce, 2003).

Typically they have a compact stout body (Fig. 1) with a triangular dorsal fin, brown to grey or even black dorsal and light-grey to white ventral coloration with darker lines running from the mouth to the flippers (Bjørge and Tolley, 2009). In the North Atlantic they usually reach a length of 141–149 cm and weight of 46–51 kg for males and 153–163 cm, 55–65 kg for females (reviewed in Lockyer, 2003). However, those parameters vary for individual populations (Lockyer, 2003). In German waters mean length is 142.7 cm and mean weight was 43 kg in mature animals (both sexes) from the North and Baltic Seas combined (Benke et al., 1998).

Sexual maturity is reached at a body length of about 138 - 147 cm for females and 127 - 135 cm for males at around 3 - 4 years of age (reviewed in Lockyer, 2003). The birth period in the North Sea takes place mainly in June and July while in the Baltic it occurs one month later (Hasselmeier et al., 2004). With a pregnancy rate of 0.7 - 1 per year, a gestation length of 10 - 11 month, lactation period of probably > 8 month (reviewed in Lockyer, 2003) and mating occurring approximately one month after parturition, females are often lactating and gestating simultaneously (Siebert et al., 2012).



Fig. 1 Harbour porpoise (*Phocoena phocoena*). Top: Typically only the triangular-shaped dorsal fin can be seen during surfacings (© Michael Dähne/ITAW). Bottom left: Colouration is usually grey to brown with lighter white-grey on the ventral side (© Michael Dähne/Dolfinarium Harderwijk, NL). Bottom right (© Katharina Brandt/Dolfinarium Harderwijk, NL): The melon, a fat body, located between the blowhole and the tip of the jaws functions as an acoustic lens for sending echolocation clicks with a narrow sound beam (Au, 1993).

Harbour porpoises can live up to ~24 years, but less than 5 % of the animals reach an age of 12 or more years (reviewed in Lockyer, 2003). Causes of deaths are most often by-catch in fisheries (Jepson et al., 2000; Siebert et al., 2001) followed by parasitic and bacterial infections of the lungs, bronchopneumonia, septicaemia, dystocia, perinatal

death and emaciation in stranded animals (Lehnert et al., 2005; Siebert et al., 2001). Porpoises from waters of Greenland, Iceland and Norway with lower anthropogenic activities showed less infectious diseases of the respiratory tract than porpoises from German waters (Lehnert et al., 2013; Siebert et al., 2006; Wunschmann et al., 2001). Furthermore animals from Greenland and Iceland had less bacterial growth than animals from German and Norwegian waters (Siebert et al., 2009). Pathological investigations of the ear showed that porpoises are regularly infected by parasites and inflammatory, degenerative lesions can be found (Lehnert et al., 2005; Seibel et al., 2010; Siebert et al., 2001, 2012; Wohlsein et al., in prep).

Like all other odontocetes harbour porpoise use echolocation for finding prey (DeRuiter et al., 2009; Miller and Wahlberg, 2013; Verfuß et al., 2009) and for orientation (Verfuß et al., 2005). The emitted signals, echolocation clicks, are narrow-band intense ultrasonic signals with a narrow sound beam (Goodson and Sturtivant, 1996; Møhl and Andersen, 1973). It has been proposed, that these clicks are also used for communication (Clausen et al., 2010).

Porpoises of the German Baltic and North Sea belong to the North Atlantic subspecies *Phocoena phocoena phocoena*, which is one of four subspecies considered at the moment (Hammond et al., 2008). The others are *P. p. vomerina* in the eastern North Pacific and *P. p. relicta* in the Black Sea (Sea of Azov) according to Gaskin (1984) and a proposed unnamed subspecies in the western North Pacific (Bjørge and Tolley, 2009; Hammond et al., 2008).

Harbour porpoises in German Baltic and North Seas

Research on the genetics of harbour porpoises in the North Atlantic suggests a complex population structure with 13 population units (Bjørge and Tolley, 2009) although the structure might be even more complex (Andersen, 2003). Morphological, genetical and toxicological studies indicate that several subpopulations of harbour porpoises occur in the North Sea, Skagerrak, Kattegat, Danish Belt Sea and inner Baltic Sea (Andersen, 1993; Andersen et al., 1997, 2001; Berggren et al., 1999; Börjesson and Berggren, 1997; Galatius et al., 2011, 2012; Huggenberger et al., 2002; Tiedemann et al., 1996; Wiemann et al., 2010). There are no clear boundaries between individual subpopulations in the North Sea/North Atlantic although genetic differences were found between geographic regions (e.g. Andersen et al., 2001; Tolley et al., 1999; Wang and Berggren, 1997). However, within the wider Baltic Sea area (Fig. 2) three subpopulations are currently recognized (Hammond et al., 2008):

1. The subpopulation of the **North Sea (NS)** extends most probably into the Skagerrak bordering the Kattegat. This subpopulation is deemed to show an alternating pattern of habitat use (Sveegaard, 2011) with
2. the subpopulation of the Kattegat, around the Danish Belt Sea extending into German waters of the Kiel and Mecklenburg Bights, but mostly in **inner Danish waters (IDW)** and
3. the subpopulation of the **Baltic Proper (BP)** with its presumed westerly borders of the Limnham and Darß Sill.

A large-scale survey for assessing the distribution and abundance of harbour porpoises has been carried out approximately every 10 years, starting with the European project SCANS (Small Cetacean Abundance in the North Sea) covering an area of 1,040,000 km² with shipboard and aerial surveys arriving at an abundance estimate of 341,366 porpoises with a CI (95 % confidence interval) of 260,000 – 449,000 in 1994 (Hammond et al., 2002). The second survey SCANS II (Small Cetaceans in the European Atlantic and North Sea) covered an even larger area of 1,370,114 km² but arrived at a similar abundance estimate of 375,358 animals (CI = 256,304 – 549,713) in 2005 (Hammond et al., 2013). The distribution of porpoise detected in 1994 differed considerably from distribution patterns in 2005 (Hammond et al., 2013). In 1994 density surface modelling showed hot spots along the coast of Scotland and around the Danish mainland. Distribution shifted in 2005 towards a hot spot off the English coast with high densities also in Dutch and Belgian waters. This shift indicates most probably that harbour porpoises use the North Sea differently over the years probably due to differences in prey availability (Hammond et al., 2013).

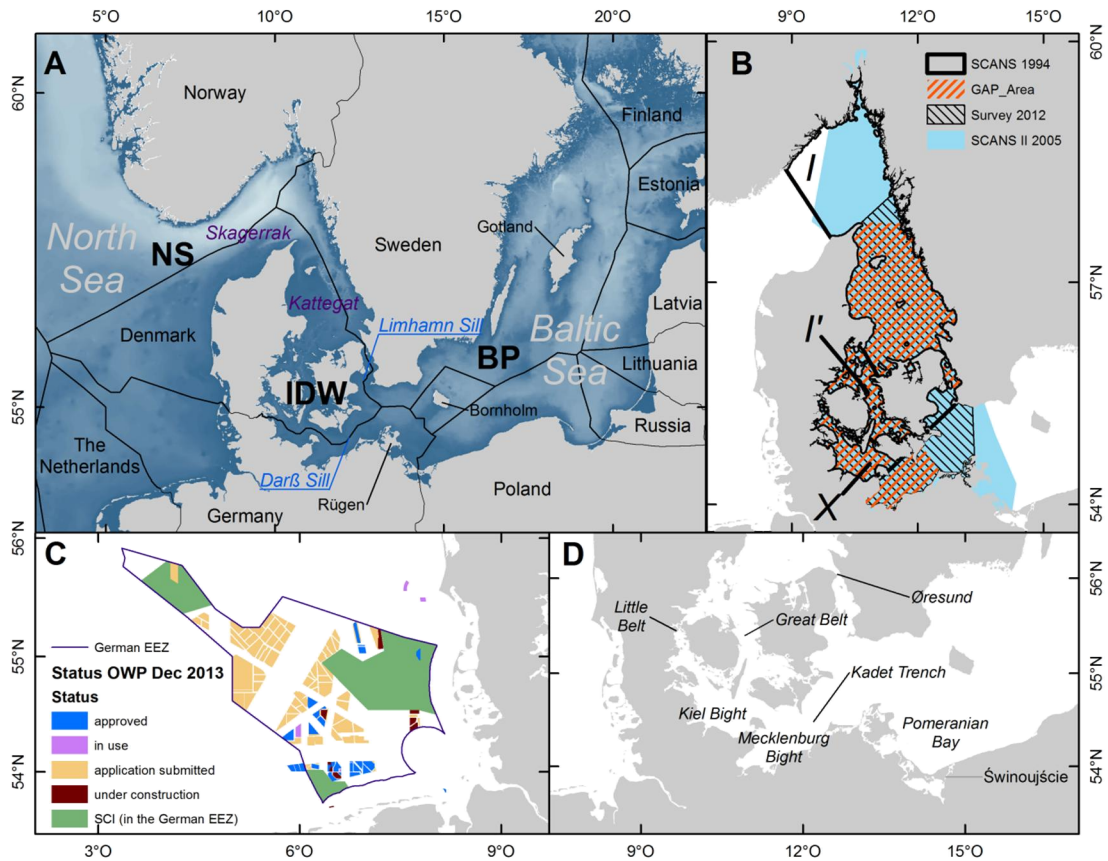


Fig. 2 Maps of the study area. A) Overview of North and Baltic Sea with overlaid bathymetry, NS – North Sea subpopulation, IDW – inner Danish waters subpopulation, BP – Baltic Proper subpopulation. B) Map of the Survey areas for the last abundance surveys in the Belt Sea area in 1994 (SCANS, subareas surveyed with ship - I and plane - I', X), 2005 (SCANS II, area S shipboard survey) and 2012 (shipboard survey). Furthermore the GAP-area that ASCOBANS proposed as putative population area of IDW-animals is marked (ASCOBANS, 2012). C) Protected Sites of Community Importance (SCI) and offshore wind farm projects in the EEZ of the German North Sea and adjacent areas. D) Oceanographic features of the study areas in the German Baltic Sea.

To analyse the potential causes of distributional changes large-scale monitoring must be carried out multiple times a year as published by Gilles et al. (2009b, 2011) and Scheidat et al. (2008). For the **German North Sea** (Fig. 2A and C) abundance of porpoises was estimated based on aerial surveys from 2002 to 2006 in spring at 55,048 animals (CI = 32,395 – 101,671), in summer at 49,687 animals (CI = 29,009-96,385) and in fall at 15,394 animals (CI = 8,906 – 29,470) showing a strong seasonal and spatial variation (Gilles et al., 2009b). Hot spots in German Waters were found at Sylt Outer Reef, where also the highest number of calves was registered, and Borkum Reefground (Gilles et al., 2009b). Porpoise density was associated to different abiotic and biotic factors like distance to coast, water depth, residual currents, surface chlorophyll concentrations and nitrogen, showing that porpoise occurrence can be predicted based on these variables (Gilles et al., 2011). In more recent studies it has been shown that porpoises also use coastal rivers more frequently (Wenger and Koschinski, 2012).

For the **IDW subpopulation** (Fig. 2A, B, C) the large-scale surveys SCANS and SCANS II did not cover the larger Baltic area according to presumed subpopulation boundaries (see Fig. 2B). During the SCANS surveys in 1994 an estimate of 36,046 animals and a density of 0.725 animals/km² with a coefficient of variation (CV) of 0.34 was estimated for the surveys block I from shipboard surveys. For I', a subarea of I, 5,262 animals and a density of 0.644 animals/km² (CV = 0.25) and for block X 588 animals and a density of 0.101 animals/km² (CV = 0.48) were estimated using aerial surveys (Hammond et al., 2002). During the shipboard surveys for SCANS II in 2005 the abundance in area S was estimated at 19,129 animals corresponding to a density of 0.28 animals/km² (CV = 0.36). Although the estimates of SCANS and SCANS II for a sub-area within putative population boundaries were not significantly different from each other at a 5 % error level, they pointed towards a decline with potentially serious consequences for the IDW-subpopulation (Teilmann et al., 2011). Within a third shipboard survey in 2012 abundance in the survey area (Fig. 2B) was estimated at 40,475 animals corresponding to a density of 0.786 animals/km² (CV = 0.24, Viquerat et al., 2014). The results however also highlight that future surveys should take population boundaries into account by either using density surface modelling to predict the abundance of the population of interest (Viquerat et al., 2013, abundance for the GAP-area, Fig. 2B, was estimated at 30,727 animals with a CV of 0.2188) or by restricting the survey area to putative population boundaries (Sveegaard et al., 2013).

The **BP subpopulation** (Fig. 2A and D) has most probably been critically endangered for at least two decades. Hiby and Lovell (1996) estimated the abundance of harbour porpoises in the Baltic Proper west of the Darß Sill and south of the Limhamn Sill (in the west) and south of Gotland (in the east) at 599 animals (CI 200 – 3,300) using a probably unrealistic group size estimate (Berggren et al., 2002) of 1.0 animals per group, which was based on three primary sightings along the Swedish coast in 1995. Berggren et al. (2002) used group size estimates from bordering waters of the Kiel and Mecklenburg Bight (1.2 animals per group) and Skagerrak-Kattegat-Great Belt area (1.5 animals per group) to calculate an abundance of 718 and 898 animals with lower confidence limits at 450 and 557 animals respectively. While this survey excluded the coastal waters of Poland a second attempt in 2002 (Berggren et al., 2004) included those, but had only two primary sightings along the Swedish coast resulting in a porpoise pod or group

abundance estimate of 93 pods (CI = 10 – 460) and highlighting that there was no increase in porpoise abundance after 8 years. No attempt to estimate group size was made for this survey, thus this group abundance is comparable to the 599 animals/groups in 1995 (except for the area surveyed), but the estimates were not statistically significantly different (Berggren et al., 2004). The results furthermore indicated that visual count surveys, while being the sole methodology to estimate abundance at that time, might not be the appropriate tool to monitor porpoises in the inner Baltic due to the extremely low sighting rates. Gillespie et al. (2005) used a combined approach of traditional visual and acoustic techniques and saw one porpoise close to Świnoujście on the Polish coast and reported three acoustic detections (two close to the Darß Sill and one on the Swedish coast). One acoustic registration was confirmed, but off effort on the Polish coast. While this survey did not calculate new abundance estimates, it confirmed the status of harbour porpoises in the Baltic Proper as being critically endangered.

The differentiation of the IDW and BP subpopulations has been questioned at times (Berggren and Wang, 2008; Palmé et al., 2008a, 2008b) but when considering the precautionary principle in conservation efforts it becomes clear, that the BP subpopulation must be considered as a management unit (Moritz, 1994, 1999) in conservation efforts as suggested by Wiemann et al. (2010). In the past, direct takes (Kinze, 1995; Skóra et al., 1988), incidental by-catch (Kinze, 1994; Kuklik and Skóra, 2003; Määttänen, 1990), sightings (Benke et al., 1998; Kock and Benke, 1996; Määttänen, 1990; Skóra et al., 1988) and strandings (Kröger, 1986) indicate that porpoises were abundant throughout the Baltic Proper with gradually decreasing densities towards northerly waters (reviewed in Koschinski, 2001).

Anthropogenic and natural stressors influencing porpoise abundance and distribution

Gaskin (1984) already noted that specifically *P. p. relicta* and the subpopulation in the inner Baltic Sea “appear to be in a critical condition”. The reasons are unclear, but are most probably caused by a multitude of factors that are either of natural or anthropogenic origin. First fossils of Baltic harbour porpoises found in Sweden dated back to 9600-7000 before now, and porpoises were recorded frequently in coastal areas of the western Baltic Sea in times dated back to 7500 – 5700 years before now (Sommer et al., 2008). In these times porpoises also used the Gulf of Bothnia and Finland, but around 4000 before now regressed towards western Baltic waters (Sommer et al., 2008) probably linked to the Littorina transgression (Björck, 1995; Schmölcke et al., 2006). These results indicate that there was already a large fluctuation in area use of porpoises in the Baltic Proper without large anthropogenic influences before recent times.

A **natural stressor** for harbour porpoises in the Baltic is ice formation in inner Baltic waters due to low salinity in this large brackish water body (Granskog et al., 2006; Seinä and Palosuo, 1996) preventing porpoises from breathing at the water surface in strong winters throughout the large Baltic basins (Koschinski, 2001). Prey availability may be another natural stressor, determining largely where porpoises occur at which time of the year. Although it is most probably one of the largest influences on harbour porpoises

only little knowledge on its relative importance is available to date. For example anecdotal knowledge of Danish fishermen suggests that porpoises follow herring into the Baltic Sea in spring and move out again in autumn. However, this seasonal migration and following of prey species was unproven until recently due to work presented in chapter 1 and by Sveegaard et al. (2012). One very difficult aspect in showing a relationship between harbour porpoises and their prey has been that estimating prey availability is very difficult. However, a large number of studies have used abiotic and biotic factors like temperature, salinity and chlorophyll as predictors for habitat suitability for cetaceans and used these variables as a proxy for prey availability (e.g. Anderwald et al., 2012; Cañadas et al., 2002, 2005; Gilles et al., 2011). Harbour porpoises are apex predators of the southern North Sea and Baltic Sea and are believed to have no natural predators themselves. Recent reports, however, indicate that grey seals mutilated harbour porpoises stranded in Belgium (Haelters et al., 2012). Direct evidence for predation and scavenging was reported from France (Bouveroux et al., 2014). Further, around the UK bottlenose dolphins *Tursiops truncatus* are known to kill harbour porpoises (Barnett et al., 2009; Wilson et al., 2004). Finally, infectious diseases in wild animals are a natural stressor to a certain extent. However harbour porpoises from German waters suffer more often from infectious diseases in comparison to other areas, so that the level of infectious diseases cannot be considered to be natural (Siebert et al., 2001, 2006, 2009; Wunschmann et al., 2001).

Anthropogenic stressors affecting porpoises have most probably changed over time. Porpoises, like other cetaceans, are vulnerable to prey depletion due to overfishing and habitat degradation (DeMaster et al., 2001), pollution in terms of heavy metals (Das et al., 2006a; Harms et al., 1978; Joiris et al., 1991; Siebert et al., 1999) and polychlorinated biphenyls and other toxicological substances (Beineke et al., 2005, 2007; Bruhn et al., 1999; Jepson et al., 2005; Siebert et al., 1999; Thron et al., 2004; Weijs et al., 2011; Yap et al., 2012), incidental catch in fishing gear (Berggren et al., 2002; Kock and Benke, 1996; Lockyer and Kinze, 2003; Vinther and Larsen, 2004; Vinther, 1999) deliberate catch in the Baltic Sea before and during World War II (Kinze, 1995; Skóra et al., 1988), anthropogenic noise from pile-driving for offshore construction work (Bailey et al., 2010b; Brandt et al., 2011; Dähne et al., 2013; Tougaard et al., 2009a), seismic surveys (Thompson et al., 2013), shipping (Terhune, 2013) and acoustic harassment devices (Brandt et al., 2012, 2013; Johnston, 2002; Olesiuk et al., 2002) as well as habitat changes and changes in prey distribution due to climate change (Thompson et al., 2007).

Echolocation in harbour porpoises

Sound travels approximately 4.5 times faster in water (~1.500 m/s) than in air (~340 m/s) and is much less attenuated than light and radio waves making it an ideal method for communication and orientation (Urlick, 1983). Porpoises use short pulsed sounds with a frequency between 120 and 140 kHz (Kamminga and Wiersma, 1981; Kamminga et al., 1996, 1999; Villadsgaard et al., 2007) for echolocation (Au, 1993). This primary sense is used almost constantly with only short periods of silence (Akamatsu et al., 2007). The emitted clicks show a L_{p-p} (sound pressure level peak to peak) of 178 - 205 dB re μ Pa measured on porpoises in the wild in comparison to clicks of animals in captivity of 129 – 174 dB re μ Pa (Linnenschmidt et al., 2012a). In addition to adjusting the emitted sound level during echolocation to target distance (automatic gain control, Linnenschmidt et

al. 2012b) porpoises can also adjust their hearing threshold to keep the amplitude of the “echo-evoked auditory brainstem response” constant when echolocating towards targets of differing distance (Linnenschmidt et al., 2012a). Porpoises are furthermore able to adjust the beam width of their sonar beam (Amundin, 1991; Koblitz et al., 2012).

Verfuß et al. (2005) showed that porpoises use landmarks for navigational tasks to orientate themselves in the water. Furthermore, they utilise echolocation for finding and catching prey in the water column (DeRuiter et al., 2009; Verfuß et al., 2009). Porpoises may also use echolocation click like sequences for communication tasks (Clausen et al., 2010). A low frequency but also low energy component of the clicks was also suggested to be used for communication purposes (Verboom and Kastelein, 1995). However, this function is not very likely, since the active space of these signals will be much smaller than for the actual transmitted frequency and therefore the low frequency component is most likely an artefact of sound production (Hansen et al., 2008).

Newer findings suggest that echolocation activity is linked to diving behaviour and that porpoises use their biosonar with different intensity at different times of the day (Linnenschmidt et al., 2012c). Echolocation breaks in that study reached a maximum of 1,300 seconds (~22 minutes, measured with an acoustic tag on one animal). However, this long silence may be an outlier, since the two other animals showed much shorter maximum breaks of 236 s and 99 s (Linnenschmidt et al., 2012c). Biosonar activity seems to also be reduced when porpoises are presumably sleeping during parabolic dives, covering approximately 5 % (up to 10 %) of their time (Wright et al., 2013b). Parabolic dives were mostly performed during day time and contained more than 10 clicks (indicating ‘active periods’) mostly during night time (Wright et al., 2013a). These results indicate diel behaviour, which has also been observed in the wild, using echolocation click loggers in Bloody Bay, Scotland (Carlström, 2005), around offshore platforms (Todd et al., 2009), as monitoring tools in the Baltic Sea (Schaffeld, 2011) and using acoustic tags on two porpoises (a third one did not show diurnal behaviour; Linnenschmidt et al., 2012c). One explanation for diel patterns might be prey availability due to vertical migration of preferred prey species such as herring (Cardinale et al., 2003; Hansson et al., 1990; Huse and Korneliussen, 2000) and cod, which depend on the vertical migration of zooplankton (Hays, 2003). At night porpoises may also have an advantage hunting for prey species, which depend on visual navigation (Schaffeld, 2011).

Acoustic monitoring methods and their application for harbour porpoises

Acoustic monitoring in cetacean research is a relatively new field. Low frequency stationary long-term deployments are used for monitoring baleen whales (Castellote et al., 2012; Gavrilov et al., 2012; Hatch et al., 2008; Samaran et al., 2013), using one or more hydrophones for localization tasks. Towed hydrophone systems are usually used in combination to visual ship board surveys for odontocetes (Boisseau et al., 2007; Gillespie et al., 2005; Li et al., 2009; Thomas et al., 1986; Yack et al., 2013) and mysticetes (e.g. Boisseau et al., 2008; Gedamke et al., 2001; Whitehead, 2009).

In order to use long-term acoustic monitoring for cetaceans two problems needed to be solved. One major problem to overcome was the development of techniques to hold the massive amounts of data created by recording continuously on high sampling rates. For capturing porpoise echolocation accurately it is necessary to record above the Nyquist

frequency (two times the highest frequency to be sampled, for porpoises ~140 kHz), i.e. about 300 kHz to be conservative. At such high sampling frequencies, only short periods of data already require large storage (if each value of one channel is stored at 16-Bit accuracy, 1 sec = ~ 600 kByte, 1 minute ~34 MByte, 1 hour ~2 GByte, 1 day ~ 48 GBytes, 1 month ~ 1.4 TBytes). The other issue for long-term recordings was the reduction of energy requirements used for internal processing.

The first instrument available for porpoises was the 'Proto-POD' designed in 1996, which exhibited still large signal processing problems (Harland, 2006). The T-POD (timing – porpoise detector, Chelonia Ltd., UK) later overcame most of these issues and was the first instrument to be applied in large-scale studies such as monitoring of small odontocetes around offshore wind farms during construction and operation (Brandt et al., 2011; Brasseur et al., 2004; Carstensen et al., 2006; Scheidat et al., 2011; Teilmann and Carstensen, 2012; Tougaard et al., 2009a) around gas platforms (Todd et al., 2009), to analyse the behaviour of porpoises with respect to harassment devices (Carlström et al., 2009; Cox et al., 2001; Leeney et al., 2007) and chemically enhanced gill nets used in by-catch reduction (Cox and Read, 2004; Koschinski et al., 2006), as well as for monitoring purposes (Berrow et al., 2009; Verfuß et al., 2008). The T-POD utilises the fact that porpoise echolocation clicks are produced in a frequency band, where other natural sounds are fairly uncommon and compares the energy content of this frequency band (around 130 kHz) to the frequency band around 90 kHz, where natural noise is also uncommon (Wenz, 1962). If a certain ratio between those energy contents is exceeded the event is recorded as the time of occurrence and duration of the signal. Since not a full waveform is recorded, this method saves memory space as well as battery power. However, since sound is not recorded, this approach makes it difficult to assign sensitivity to different devices and hence requires another form of calibration of the instruments (Kyhn et al., 2008 and chapter 2, this study). To overcome disadvantages of traditional visual surveys (availability bias is high because porpoises can only be seen in 20-30 % of the time at the water surface and perception bias may vary for each observer) methods to use T-PODs for abundance estimates have been suggested (Kyhn et al., 2012). One major short-coming of the T-POD was that it was not possible to simultaneously detect porpoises and dolphins in locations where both species occur. It was however possible to set the instruments to alternating settings, so that for times when a POD is set to dolphin settings it would record only dolphins, and during porpoise settings would record porpoises and on-axis clicks of dolphins (Simon et al., 2010). Similar to the T-POD the A-Tag (Acoustic Tag, Little Leonardo, JP), a stereophonic device originally developed to be attached to odontocetes (e.g. Akamatsu et al., 2007), works as an energy detector and can be deployed stationary (Sasaki-Yamamoto et al., 2013).

In 2008, the C-POD (short for cetacean POD) was presented by Chelonia Ltd as the replacement instrument for the T-POD. The C-POD addressed major shortcomings of the T-POD. Its detection principle as a tonal click detector (see chapter 4 this thesis and www.chelonia.co.uk¹) allows for detecting and classifying a multitude of species (quasi-) simultaneously. It is searching continuously for events with sufficiently small bandwidth in the stream of sound acquired by the hydrophone. Of those events it records the

¹ accessed: 13.10.2013

amplitude in 8 Bit resolution, the frequency calculated using zero crossings, the duration of the signal as the number of logged cycles, bandwidth and parameters of the envelope calculated using different parts of the signal to get information whether the signal is for instance a sweep. With this information more accurate species identification should be possible. First studies using C-PODs have been published recently, analysing the displacement radius of seal scarers for porpoises (Brandt et al., 2012), the impact of seismic surveys on porpoises (Thompson et al., 2013), as well as to test whether environmental DNA is an appropriate tool for monitoring Baltic harbour porpoises (Foote et al., 2012), to investigate whether porpoises enter riverine habitats more frequently (Wenger and Koschinski, 2012) and to evaluate the use of pingers for by-catch reduction (Hardy et al., 2012). Tests for the estimation of a detection radius of C-PODs have so far only been performed for bottlenose dolphins (Nuuttila et al., 2013).

T-PODs, C-PODs and A-Tags have been particularly useful for studies of species that are currently endangered such as New Zealand's Hector's dolphins *Cephalorhynchus hectori* (Rayment et al., 2009) and its critically endangered subspecies the Maui's dolphin *Cephalorhynchus hectori maui* (Rayment et al., 2011), the Vaquita *Phocoena sinus* in Mexico (Jaramillo-Legorreta et al., 2012) and the Ganges River dolphin *Platanista gangetica* (Sasaki-Yamamoto et al., 2013). For the Baltic harbour porpoise PCLs (Porpoise Click Loggers, Aquatec Ltd, UK), a device similar to the T-POD, were tested in Danish (Kindt-Larsen, 2008) and Swedish waters (Wennerberg, 2007) in addition to the other more common devices.

Sensitivity of porpoises towards sound

Human impacts on the marine environment include, amongst others, the emission of sound in the form of shipping noise, dredging, oil- and gas exploration by seismic surveys, explosions in military activities and to remove ordnance, sonars, echo sounders, fish finders, harassment devices in aquaculture and gill net fisheries, pile-driving and vibro-piling for offshore installations, drilling and research (Richardson et al., 1995). All of these noise sources contribute to an increase of underwater noise, which has been suggested to equal a tenfold rise in noise levels over the last decades (Hildebrand, 2004). Ship noise alone is suspected to have increased ambient ocean noise levels by 12 dB (Hildebrand, 2009). Whether these sounds have an impact on biota depends strongly on their nature (impulsive or continuous noise), their energy content, duration, rise time, and whether the animals concerned can actually perceive these sounds (Southall et al., 2007).

The basics of the possible impacts of sound on marine mammals are described in detail in Richardson et al. (1995) and Southall et al. (2007). A major concept in this framework are the '**zones of noise influences**' broadly distinguishing between the 'zone of audibility', the 'zone of responsiveness', the 'zone of masking' and the 'zone of hearing loss, discomfort or injury' (Richardson and Malme, 1995), which are mostly depicted as concentric circles of gradually decreasing size around a sound source. Although this concept still very much holds true, it can be expanded using results of newer research, for example to also include effects on the equilibrium organ. It can also be adapted to fit different definitions for injury. With respect to behavioural responses it has been suggested, that those reactions will not always follow a strict dose-response function

due to context (for instance the activity state of the animal), relative sound levels due to variations in background noise and hearing threshold of the individual and effect being either chronic or acute (Ellison et al., 2012).

Hearing abilities of harbour porpoises were first estimated by Andersen (1970) and Kastelein et al. (2002, 2010) using behavioural response paradigms and later using auditory evoked potentials (Lucke, 2008; Lucke et al., 2009; Siebert et al., 2013). The behavioural audiograms showed that harbour porpoises have their best hearing sensitivity between 16 and 140 kHz with a hearing threshold of approximately 40 – 60 dB re μPa . However, porpoises can also hear frequencies below 10 kHz (tested down to 250 Hz) with a gradual drop off in sensitivity of approximately 10 dB per octave (Kastelein et al., 2002) although newer data suggest better hearing capabilities between 2 and 10 kHz (Kastelein et al., 2010). Above 140 kHz sensitivity has a very sharp drop off of approximately 260 dB per octave (Kastelein et al., 2002).

Intense noise has the potential to elicit a **behavioural reaction** in harbour porpoises. Behavioural reactions can range from a startle response, a sudden change in behaviour usually in form of a reflex, to large-scale displacement effects. A startle response in porpoises has been demonstrated by Kastelein et al. (2012c) in response to mid frequency up-sweeps as used in mid and low-frequency sonars at received SPLs (sound pressure level) of 99 to 133 dB re μPa depending on the transmitted frequency. An aversive behavioural reaction of harbour porpoises towards impulsive airgun sounds was reported by Lucke et al. (2009) at an SEL (sound exposure level) of 145 dB re $\mu\text{Pa}^2\text{s}$. The authors however argue that this may be an elevated level due to the fact that the animal was actually trained and rewarded for tolerating the exposure. Pile-driving sounds, as another impulsive sound source, are audible to harbour porpoises over at least tenth of kilometres (Kastelein et al., 2013b; Madsen et al., 2006) and can elicit a direct displacement effect over approximately 20 km distance (Brandt et al., 2011; Tougaard et al., 2009a, chapter 5 this thesis). Pile-driving will be used extensively over the next decades in Europe to install the foundation for offshore wind turbines (Breton and Moe, 2009). This installation process will most likely have more severe effects than the operation period of wind farms (Madsen et al., 2006). This is substantiated by results of noise recordings on three offshore wind farms in Denmark, showing that harbour seals can hear the operating turbines over much larger distances of up to several kilometres than porpoises at approximately 20 - 70 m (Tougaard et al., 2009b). In contrast, during the operation period non-sound related impacts like an artificial reef effect or that the wind farm is a sheltered area with reduced fishing effort may have a larger effect on porpoises (Scheidat et al., 2011). Displacement effects have also been documented for pingers, devices to displace porpoises from passive fishing gear (Carlström et al., 2009; Culik et al., 2001) as well as for the much louder seal scarers at distances up to 7.5 km (Brandt et al., 2012, 2013; Johnston, 2002; Olesiuk et al., 2002).

Harbour porpoises have a low limit for a **temporary threshold shift**² (TTS) compared to other cetaceans making them highly susceptible to noise effects (Lucke et al., 2009). A

² A threshold shift is a change in hearing sensitivity compared to normal hearing capabilities (minimum level perceivable = threshold). Loud sounds can elicit a temporary threshold shift or may result in a permanent threshold shift.

porpoise in human care experienced the onset of TTS for an impulsive airgun sound (with similar frequency characteristics as a pile driving sound) at an SEL of 164.3 dB re $\mu\text{Pa}^2\text{s}$ and a peak to peak sound pressure level (L_{p-p}) of 199.3 dB re μPa (Lucke et al., 2009). For detonations, another impulsive but even more broad band sound source, a porpoise showed a detection threshold at an SEL of ~ 60 dB re $\mu\text{Pa}^2\text{s}$ which would result in approximately 90 dB signal excess in 100 km distance from the detonation (Kastelein et al., 2012a). Therefore, porpoises can hear these signals at even larger distances. Experiments using continuous octave-band noise centred around 4 kHz showed that the tested porpoise experienced the onset of TTS after an exposure to an SPL of 124 dB re μPa for 7.5 min, showing that continuous noise also has the potential for adverse effects in harbour porpoises (Kastelein et al., 2012b). The recovery time to return to pre-stimulation thresholds varied from 4 to under 96 minutes, indicating that a normal hearing sensitivity is regained after sufficient time without noise influences. No dedicated measurements of permanent threshold shift (PTS) have been conducted in any cetacean to date.

Acoustic techniques for mitigating negative impacts on harbour porpoises from offshore construction work

The current aim of the German Parliament is to install offshore wind turbines of a nominal capacity of 25 GW in German waters until 2030 (BMW, 2012). Assuming a rated power of 5 MW per turbine this would result in ~ 5000 wind turbines to be erected within a 22 years time span. This process started with the installation of the first offshore wind farm *alpha ventus* (chapter 5 this thesis) in 2008. Overall, about 230 turbines per year would be necessary to be installed in the German North and Baltic Seas to reach this goal. These numbers demonstrate, that if the foundations are piled without noise mitigation, displacement effects, which have so far been documented at approximately 20 km (Brandt et al., 2011; Dähne et al., 2013; Tougaard et al., 2009a) may reach population level effects on porpoises (Gilles et al., 2009b). The gravity of this situation becomes even clearer, when it is considered, that nearly all European Countries plan on building offshore wind farms in the next decades and cumulative effects of wind farms in neighbouring countries may occur.

In order to avoid these impacts, the German federal maritime and environmental agencies propose a precautionary value of an SEL of 160 dB re $\mu\text{Pa}^2\text{s}$ and L_p of 190 dB re μPa in 750 m distance to prevent injury (in terms of TTS). This value is part of the permit for each individual wind farm³ and hence the constructors must find suitable ways of minimizing the noise impact by either adapting their foundations to a low noise system (heavy foundations, drilled foundations, vibro-piling, moored swimming systems, suction buckets) or by using a noise mitigation system to attenuate the emitted signals. In addition, the permit holders are asked to take precautions to assure that porpoises are not within the potentially detrimental radius of 750 m, in which injury may occur. Thus, before pile-driving is conducted, acoustic harassment devices are to be used to displace porpoises from within 750 m of pile driving activity, usually by using a combination of

³ Furthermore, for each new wind farm project in Germany the “Schallschutzkonzept” (Noise control concept, applicable from 01.12.2013) for harbour porpoises defines these measures (see http://www.bfn.de/0319_windenergienutzung_offshore.html, accessed 09.03.2014 for more details).

pingers and seal scarers. Although it is known that seal scarers have a much larger displacement radius than needed (Brandt et al., 2012, 2013; Johnston, 2002), there is currently no alternative to using these devices. Nevertheless, they increase noise levels at sea and may be subject to habituation, which could potentially result in a reduced efficacy. Thus, direct noise mitigation measures are preferable to these displacement approaches.

A number of different noise mitigation systems have been presented so far (reviewed in Koschinski and Lüdemann 2011, Wilke et al., 2012). Except for two of these concepts (prolongation of the impulse duration using piling cushions and noise reduction by optimization of all piling components) all approaches use air filled cavities for attenuating the underwater sound. The most advanced device so far is the air bubble curtain, which emits air bubbles under water to cover the entire water column, producing a bubbly water, that reduces the sound speed and creates an impedance mismatch, resulting in reduced sound levels outside of the bubble curtain (Lucke et al., 2011; Wilke et al., 2012; Würsig et al., 2000). Within chapter 6 we tested an unconfined air bubble curtain for its efficacy to attenuate under water sound levels to guide future application and design of bubble curtains for field trials in offshore situations. Focus was set on the design as a modular system and testing of the pipe layout in terms of nozzle placement and necessary air flow rates to achieve high attenuation rates.

Main research questions

The main research questions of this thesis are the following:

1. Can stationary acoustic monitoring (SAM) be used for the conservation of Baltic harbour porpoises? How can we use SAM for regular monitoring approaches, as well as in experimental setups most efficiently?
2. What are the acoustic properties of currently employed instruments used for SAM and how do these properties influence results of environmental impact assessments as well as long-term monitoring?
3. What are the influences of the construction of an offshore wind farm on porpoises?
4. How can acoustic methods for noise mitigation be applied to effectively protect harbour porpoises from potentially harmful impulsive sounds?

Thesis outline

This thesis consists of six individual chapters, each focussing on one aspect of either the use of stationary acoustic monitoring (SAM) of harbour porpoises for describing porpoise distribution patterns in the German Baltic Sea with T-PODs (chapters 1 and 3) for conservation efforts, focussing on methodology and calibration of commonly used porpoise detectors (T-PODs in chapter 2 and C-PODs in chapter 4), using passive acoustic methods for impact studies of offshore wind farms (chapter 5) and mitigating those impacts using acoustic attenuation with bubble curtains (chapter 6). Five of these studies (chapter 1-5) were submitted and have been published in peer-reviewed journals. These chapters are identical to the published version. Each chapter contains its own list of references, plus a separate list for the general introduction and discussion.

Chapter 1

This chapter comprises the first large-scale study to assess harbour porpoises occurrence, as well as geographical and seasonal distribution patterns in German waters using stationary acoustic methods. For a period of three years up to 42 automated click loggers (T-PODs) were deployed in the German Baltic Sea to detect high frequency echolocation clicks of harbour porpoises. Automatically detected click sequences were visually verified and classified as 'porpoise', 'boat' or 'other origin'. The proportion of porpoise positive days (ppd - being days with at least one visually verified porpoise detection) per month was calculated. A matrix correlation revealed that registration rates of positions close together are more similar than data of stations recorded further away suggesting that data of individual stations describe porpoise habitat use in a larger area. A significant geographical distribution pattern was recorded with highest ppd found in the western parts of the German Baltic Sea (Kiel Bight and Fehmarn) decreasing towards the Pomeranian Bay. A seasonal pattern showing lowest detection rates in winter, increasing detections towards spring and summer and decreasing detections in fall suggested that porpoises from the Danish Belt Sea move into German waters when the abundance of herring is at its peak.

Chapter 2

Acoustical devices are commonly calibrated to reference their voltage output to a specified acoustic pressure input. This is not feasible for autonomous echolocation click detectors like the T-POD as the detection settings and mechanism may alter the output of the hydrophone. However, it is essential to calibrate them, as the detection threshold depends on hydrophone sensitivity, directionality, type of detector and settings. A calibrated detection threshold combines these values and is decisive about the detection range of individual instruments influencing the comparability of data acquired with different instruments, versions and settings. A methodology for the calibration of T-PODs, one of the most commonly used instruments for echolocation monitoring in the past decade, is presented within this chapter. Results suggest that variability of detection thresholds decrease with newer version of T-PODs. The directionality was also found to significantly improve towards an omnidirectional receiving pattern with newer version of the devices. T-PODs can be adjusted by the user to work at a specified sensitivity, a feature that works well in newer hardware versions. The relationships found were used in chapter 3 to set instruments to a unified sensitivity.

Chapter 3

The results found in chapter 1 and 2 were used within this study to describe the distribution pattern of porpoises in the Baltic Proper using a setup of 22 measuring positions equipped with T-PODs in the waters around the island Rügen. Two seasonal peaks were found in SAM data of offshore stations during winter and late summer. The central hypothesis of this chapter is that harbour porpoises from the Belt Sea and from the Baltic Proper both use the water east of Rügen, but show an alternating pattern of habitat use. Those subpopulations are known to diverge morphologically and genetically. A second hypothesis was that porpoises from the Baltic Proper may retreat into German Waters during cold winters to avoid suffocation due to ice formation in the central Baltic basins. We tested these hypotheses by splitting the data of all recording positions into three groups: 1) one position west of Rügen was used as a proxy for the occurrence of porpoises of the Belt Sea subpopulation (reference position), 2) coastal positions closer to Rügen and 3) positions in offshore waters of the Adlergrund and Oderbank. Generalized additive models built from these data showed that coastal positions were mostly influenced by occurrence of porpoises at the reference position. Offshore positions, however, showed strong influences of air temperature and the difference of air and surface water temperature, in this case used as a proxy for ice forming conditions. The results of this 2 ½ years study can be used in a conservation context, as they present for the first time data on seasonal occurrence of critically endangered Baltic harbour porpoises and their ecological preferences.

Chapter 4

In 2008 the T-POD, used in chapter 1-3, was replaced by its digital successor the 'C-POD' (cetacean POD). This shows one often overlooked critical problem using state of the art technology to acquire data of ecological importance: Long-term monitoring requires that methodology and equipment do not change over the course of the study, or comparability must be guaranteed in other ways. When C-PODs started to be used we developed a calibration procedure and applied it to 86 C-PODs in order to determine how this tonal detector performs in terms of frequency dependence and whether the previously used measures can be applied for this instrument, or must be adapted. Results showed, that C-PODs are well standardized at 130 kHz, which is not surprising, given, that the manufacturer performs his standardization process at this frequency. However, C-PODs do not show linearity in frequency response below 80 kHz and above 140 kHz. This has implications for multi-species studies, as the detection range for different species will vary. A few instruments showed larger differences from the mean peak to peak detection threshold of 114.5 dB re μPa highlighting the necessity to conduct calibration trials to find outliers.

Chapter 5

Offshore wind farms are one major opportunity to produce environmental friendly electric energy for the next decades. For Germany the number of planned and permitted offshore wind farms grows constantly. At the moment these wind farms will mostly be installed using pile-driving of large steel piles (diameter > 2 m) to install the foundations. Noise produced during these installations may affect harbour porpoises in terms of injury to the hearing system in the vicinity of the construction site and by provoking an avoidance reaction over a large area. We used large-scale aerial surveys and SAM using

C-PODs to monitor the area of the first German offshore wind farm before, during and after the installation of the piles for 12 wind turbines. Results showed a strong avoidance reaction over a 20 km radius and suggested that the duration of pile-driving has a large influence on the duration of the displacement effect. In conclusion we propose, that further research is needed for developing techniques to reduce the pile-driving effect at the source using noise mitigation measures (like air bubble curtains, see chapter 6) and investigating cumulative effects of multiple quasi-simultaneous installations in the North Sea in the context of all other anthropogenic stressors to predict population consequences.

Chapter 6

One solution to mitigate pile-driving noise at the source is the use of curtains surrounding the pile with an unconfined stream of air bubbles. This creates an impedance mismatch between water and the two phase medium of air and water in the bubble curtain, which lowers the speed of sound and creates multiple reflections as well as resonances resulting in a direct attenuation of the sound emitted. Although this methodology has been used in the past attenuation results obtained in different studies vary greatly. This suggests that not all underlying principles are well understood and can be used to predict the attenuation efficacy during field use. We conducted test tank and field trials to compare the performance achieved in laboratory studies to the results of field experiments. Tank results indicated that the factor influencing the efficacy most was the air flow rate, indicating also that the impedance mismatch is of greater importance for attenuation efficacy than resonance effects. In the field trials we achieved very good attenuation efficacy, but the test signals could not be detected in the bubble curtain self-noise at high air flow rates indicating even higher attenuation rates. Because the study was limited to using an artificial signal and sound source, we did not record any influences of sediment conduction and back propagation into the water column. In field trials the factor limiting attenuation efficacy may hence be the proportion of energy transmitted through the sediment, as this part cannot be attenuated in the water column close to the pile.

Manuscripts

1 Geographical and seasonal variation of harbour porpoise (*Phocoena phocoena*) presence in the German Baltic Sea revealed by passive acoustic monitoring

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Two harbor porpoises in the Dolfinarium Harderwijk (© Michael Dähne/Dolfinarium Harderwijk)

Geographical and seasonal variation of harbour porpoise (*Phocoena phocoena*) presence in the German Baltic Sea revealed by passive acoustic monitoring

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The harbour porpoise is the only resident cetacean species in the German Baltic Sea. Within the last several decades this harbour porpoise stock declined drastically, causing deep concern about its status. Plans of the German government for proposing Marine Protected Areas (MPAs) to implement *Natura 2000* and for assessing the impact of offshore windmill constructions on the marine environment led to an increased research effort on the harbour porpoise in German waters. For the first time, long-term passive acoustic monitoring has been conducted in the German Baltic Sea from the Kiel Bight to the Pomeranian Bay from August 2002 to December 2005. Porpoise detectors (T-PODs) have been installed five to seven metres below the water surface at up to 42 measuring positions throughout the investigated area, registering the exact times of echolocation signals of passing harbour porpoises. The proportion of monitored days with porpoise detection in each quarter of the years has been analysed. A correlation of the results with the longitude of the measuring position revealed a significant decrease from west to east in the percentage of days with porpoise detections. Comparison of data gathered in the first quarters with the third quarters of the monitoring years displayed a seasonal variation with fewer days of porpoise detections in winter time than in summer time. Nevertheless, harbour porpoises have been detected year-round at most of the measuring positions in the German Baltic Sea. The present study clearly indicates a regular use of the German Baltic Sea by harbour porpoises with a geographical and seasonal variation in the usage of the German Baltic Sea. The larger numbers of harbour porpoise detections in spring to autumn compared with winter suggests that the German Baltic Sea is an important breeding and mating area for these animals.

INTRODUCTION

Harbour porpoises occur throughout temperate shelf waters of the northern hemisphere (Read, 1999). In the Baltic Sea they were very common up to the middle of the 20th century (Schulze, 1996). While the former range of the harbour porpoise extended into the easternmost and northernmost parts of the Baltic Sea (Koschinski, 2002), the population size decreased severely within the last several decades (Kröger, 1986; Benke et al., 1998; Kinze, 1995; Siebert et al., 1996) with a drastic reduction of the porpoises' range (Koschinski, 2002). Since 1988, the harbour porpoise has been included in Appendix II of the Convention on the Conservation of Migratory Species of Wild Animals (CMS), an intergovernmental treaty (<http://www.cms.int>). The CMS initiated the Agreement on the Conservation of Small Cetaceans of the Baltic and North Seas (ASCOBANS), focusing upon the conservation status of the Baltic Sea harbour porpoise. Other international agreements such as OSPARCOM and HELCOM also consider the conservation of this species.

In the German Baltic Sea, the harbour porpoise is the only resident cetacean species (Benke et al., 1998). Long-term investigations on harbour porpoises in Germany so far have included the collection of strandings and incidental by-catches, giving the opportunity for assessing distribution and health status of these animals in the German Baltic Sea (e.g. Siebert et al., 2001; Das et al., 2004; Siebert et al., 2006), their population structure (Tiedemann et al., 1996; Huggenberger et al., 2002) and their reproductive status (Benke et al., 1998). Furthermore, incidental sightings have been collected for several decades (H. Benke, personal communication; Siebert et al., 2006).

Until recently, all abundance estimates of harbour porpoises covered the German Baltic Sea only partly, either restricted to the western part up to the Kiel Bight (Heide-Jørgensen et al., 1992; Heide-Jørgensen et al., 1993; Hammond et al., 2002) and the Darss Sill (Gillespie et al., 2003), or to the area east of the Darss Sill (reviewed in Vesper & von Dorrien, 2001). Plans of the German Government for assessing the impact of offshore windmill constructions, as well as for proposing Marine Protected Areas (MPAs) to implement

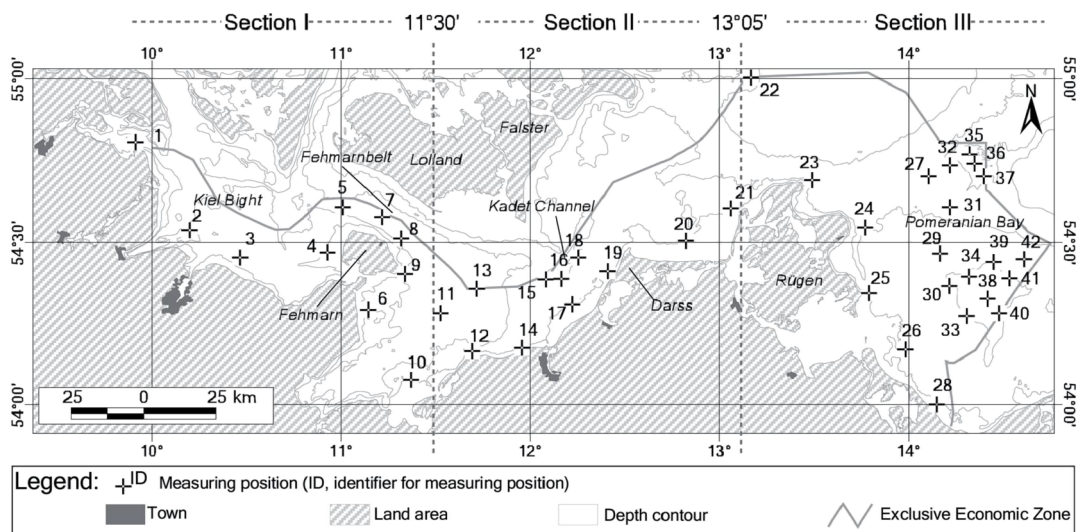


Figure 1. Timing porpoise detector (T-POD) measuring positions (crosses) in the German Baltic Sea. Longitudes 11°30'E and 13°05'E subdivide the German Baltic Sea into Sections I, II, and III for further analysis.

Natura 2000, led to an increased research effort on the harbour porpoise in Germany. In this context, Scheidat et al. (2004a, b) included the entire German Baltic Sea area in their abundance study. Results of aerial surveys conducted in 1995 and 1996, which include the entire German Baltic Sea, have also been published recently (Siebert et al., 2006).

CMS (<http://www.cms.int>) considers the harbour porpoise as a migratory species. The porpoise populations of the western North Atlantic move into coastal waters during summer. In some areas, they move offshore in winter to avoid advancing ice cover (Read, 1999). Seasonality in harbour porpoise abundance is also found around the coast of Iceland (Saemundsson, 1939) and the Faroe Islands (IWC, 1996). Historical catches in the Little Belt area of Denmark in spring and winter point towards a seasonal migration of harbour porpoises inhabiting the Baltic Sea (Kinze, 1995). Anecdotes and the historical tradition of Danish fishermen hunting those porpoises imply that the animals followed herring schools into the Baltic Sea in spring and left the inner Baltic waters, escaping from sea ice formation in autumn and winter (reviewed in Koschinski, 2002). Incidental sightings and strandings data collected in the German Baltic Sea from 1988 to 2002 and 1990 to 2001, respectively, also show seasonality when summed over the study period, with maximum numbers in July to September (Siebert et al., 2006). Nevertheless, these methods contain some bias, for example due to unequal sightings effort or due to differences in the submersion time of carcasses depending on the seasons (Siebert et al., 2006). Therefore, it has not yet been conclusively shown if, and how, harbour porpoise abundance in the German Baltic Sea changes over seasons, i.e. if seasonal migration takes place in the harbour porpoise population inhabiting the German Baltic Sea.

Like other odontocete species, harbour porpoises emit short pulsed high frequency click sounds for echolocation (Au, 1993). As an active sensory system, echolocation in

porpoises is used for orientation (Verfuß et al., 2005) as well as for foraging (Verfuß & Schnitzler, 2002). Harbour porpoise echolocation clicks are very distinct and differ from most dolphin echolocation clicks (Au, 1993). Their main energy is focused upon a small frequency bandwidth around 130 kHz (Goodson et al., 1995; Kamminga et al., 1999). The distinct and easily distinguishable click structure provides a good opportunity to set up an automatic system that specifically monitors this species, such as a porpoise detector (T-POD). The advantage of static passive acoustic monitoring with T-PODs is that the devices are suitable for long-term deployment. They register the presence of harbour porpoises over months.

The study presented here has been conducted to gain knowledge about the spatial usage of the German Baltic Sea by harbour porpoises. This knowledge provides data for proposing protection areas and gives a baseline for future monitoring programmes in areas of interest such as windmill construction or protection areas. The results of 3.5 years of year-round harbour porpoise monitoring in the German Baltic Sea are presented. The spatial and seasonal variation of the relative abundance of harbour porpoises was investigated with a network of static passive acoustic monitoring instruments, the T-PODs.

MATERIALS AND METHODS

The T-POD

Timing porpoise detectors, (T-PODs, Chelonia Ltd., Long Rock, United Kingdom) are self-contained data loggers for cetacean echolocation clicks, consisting of a hydrophone, filter and digital memory. They register, at a 10 µsec resolution, the presence and length of high frequency click sounds matching specific criteria, logging for 24 hours a day over a period of eight to ten weeks. After this period, the data are downloaded and batteries have to be replaced.

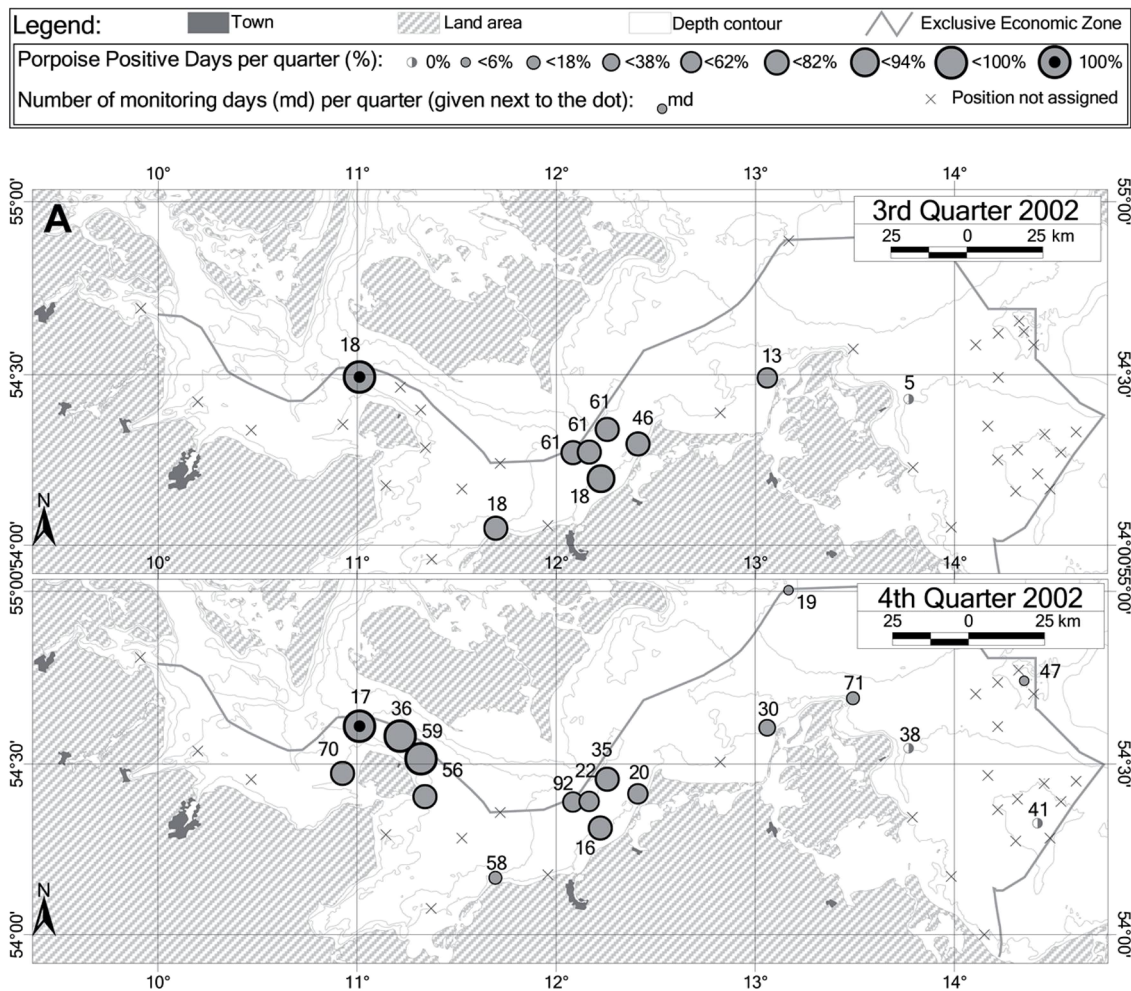


Figure 2. Percentage of porpoise-positive days per monitoring period at the measuring positions for each quarter of the years (A) 2002; (B) 2003; (C) 2004; and (D) 2005. The size of the dots is proportional to the percentage. The number of monitoring days is given next to the dots. Measuring positions at which no data were gathered for the specific quarter are marked with grey crosses.

The T-POD software comprises a train detection algorithm, that detects and then classifies trains of registered clicks according to how likely they are to be a cetacean train.

T-POD application

Up to 42 measuring positions were selected to monitor the German Baltic Sea from the Kiel Bight to the Pomeranian Bay (Figure 1) between summer 2002 and the end of 2005. This network of measuring positions contained 17 positions in 2002, and grew, especially at the beginning of 2005, to its final size. Water depth at the measuring positions ranged from 7 m up to 28 m. Measuring positions have been allocated throughout the German Baltic Sea in order to cover the area as appropriately as possible. Emphasis was laid upon proposed MPAs as well as — since 2005 — on the Pomeranian Bay. The positions met the demands of the German Water and Shipping authorities.

At each measuring position, one T-POD at a time was deployed on a mooring, fixed five to seven metres under the water surface. T-PODs of versions 2, 3 and 4 were used. The mooring consisted of a 30-kg weight and anchor connected to several surface buoys via a rope. From the beginning of the recordings in 2002 until spring 2005, the listening criteria of the T-PODs were set to *porpoise-only high sensitivity* as given in the T-POD programme (T-POD version 2: *filter A*=130 kHz, *filter B*=90 kHz, *ratio A/B*=4, *A' filter sharpness*=10, *B' filter sharpness*=18, *minimum intensity*=6, *scan limit on number (N) of clicks logged*=240; T-POD version 3: *filter A*=130 kHz, *filter B*=90 kHz, *ratio A/B*=4, *A' integration period*=short, *B' integration period*=long, *minimum intensity*=6, *scan limit on N clicks logged*=240; T-POD version 4 was not used during that time). Eventually the *ratio A/B* was set to 6, which reduced the registration of high frequency background noise.

The T-PODs were calibrated before deployment as described in Verfuß et al. (2004a,b) in order to determine

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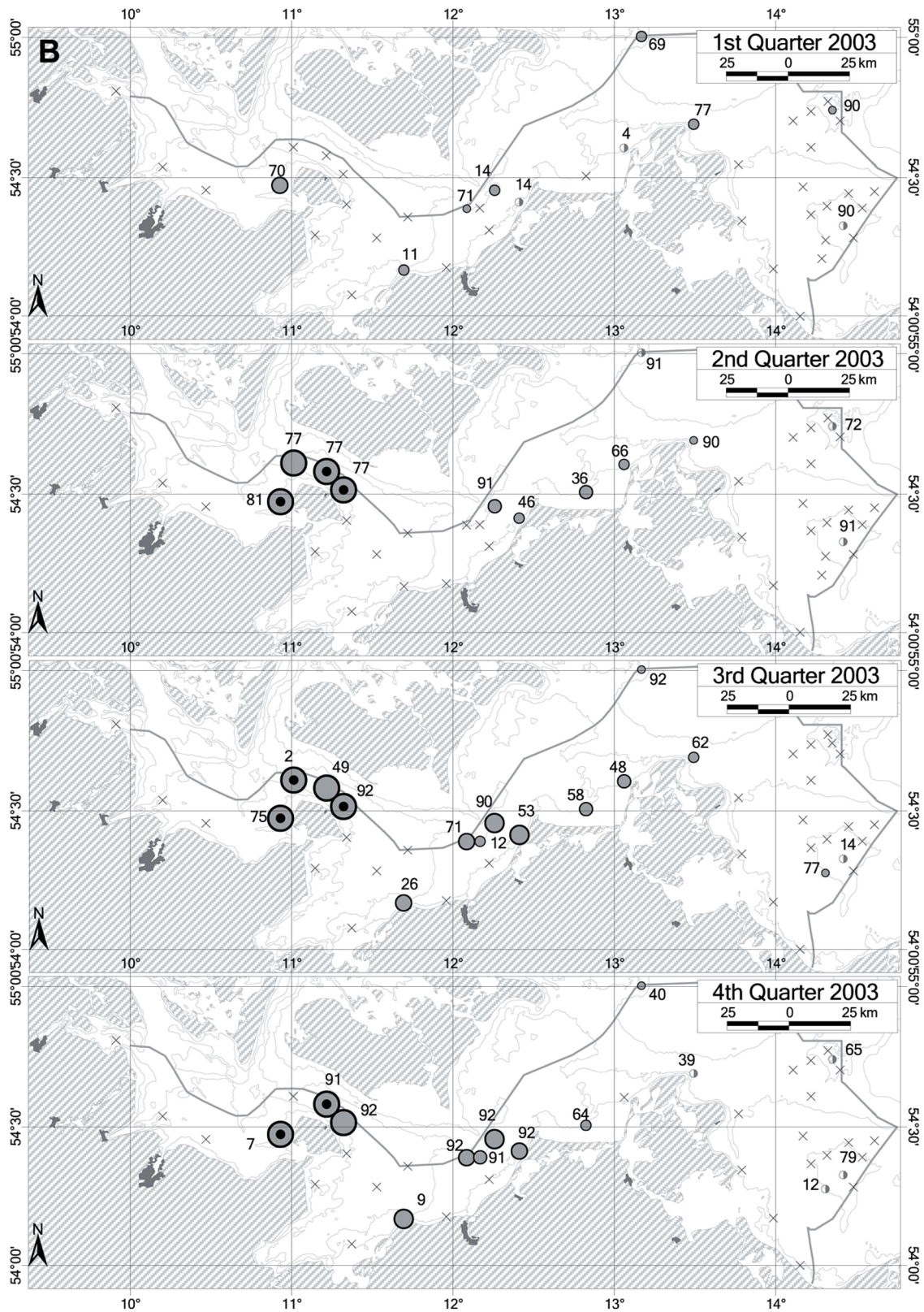


Figure 2. (continued)

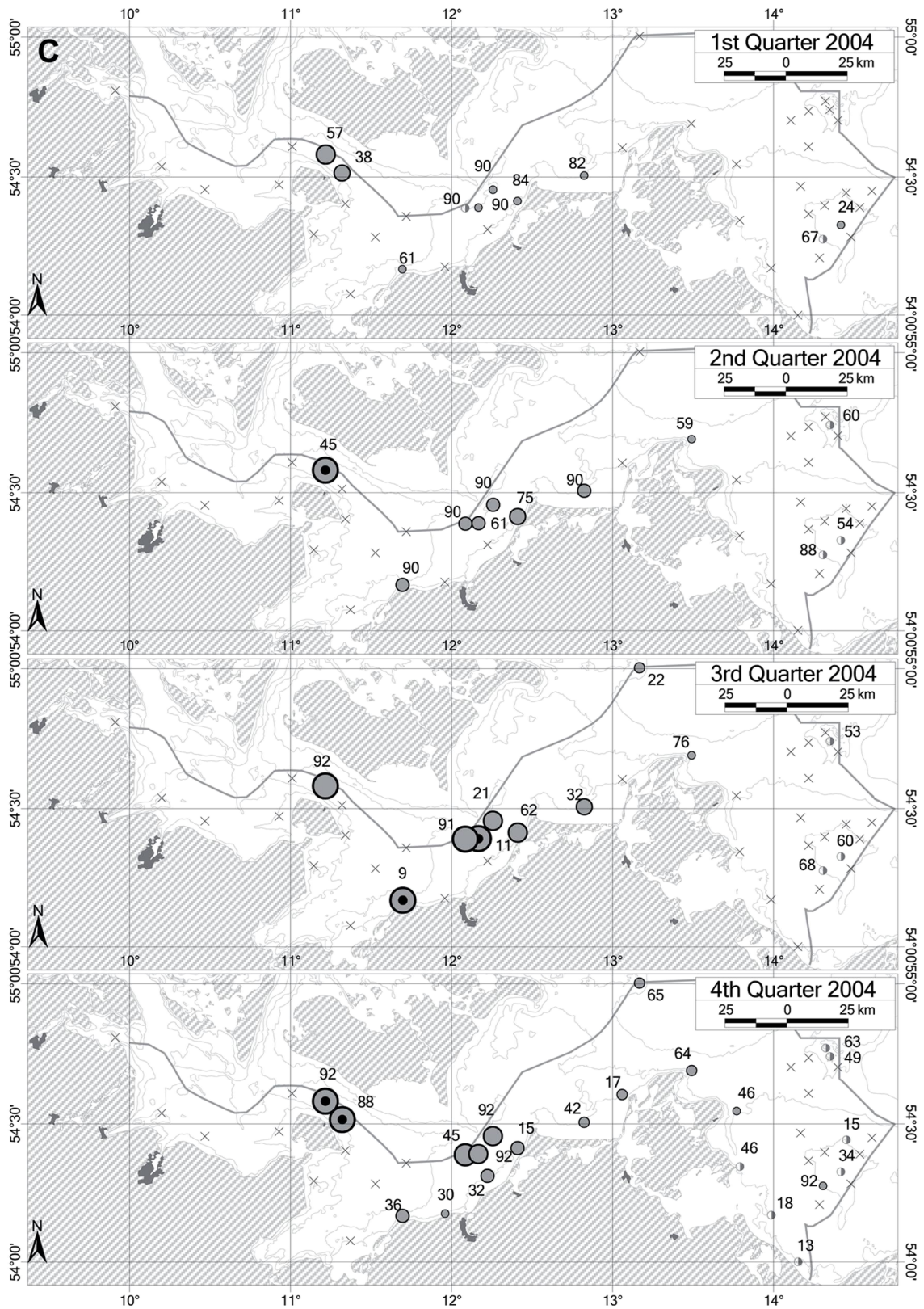


Figure 2. (continued)

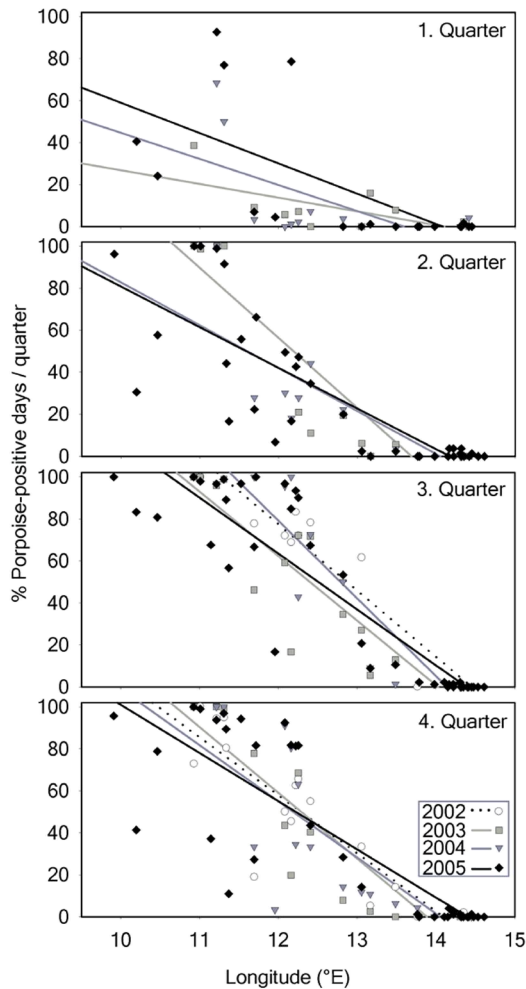


Figure 3. Percentage of porpoise-positive days per quarter of the monitoring years 2002 (circle), 2003 (square), 2004 (triangle) and 2005 (diamond), plotted against the longitude of the corresponding measuring position. The corresponding regression lines for each quarter of the years 2002 (dotted), 2003 (light grey), 2004 (dark grey) and 2005 (black) are also given.

the specific minimum receiving level up to an accuracy of ± 1 dB. This is the minimum sound pressure level that a porpoise click needs to have at the device's hydrophone to be registered. The minimum receiving level of the deployed T-PODs was in the range of 117 dB re $1 \text{ V}_{\text{pp}}/\mu\text{Pa}$ up to 144 dB re $1 \text{ V}_{\text{pp}}/\mu\text{Pa}$. From spring 2005 onwards, the T-PODs were set as close to a standard sensitivity of 127 dB re $1 \text{ V}_{\text{pp}}/\mu\text{Pa}$ as possible by adjusting the parameter *minimum intensity*. From this time onwards, also version 4 T-PODs were used, set to: *filter A*=130 kHz, *filter B*=92 kHz, *click bandwidth*=5, *noise adaptation*=++, *sensitivity*=adapted to our standard sensitivity of 127 dB re $1 \text{ V}_{\text{pp}}/\mu\text{Pa}$.

Influence of T-POD version / settings / sensitivity

Knowledge of the effect on the data of differences in the versions of T-POD, their settings and/or their sensitivity is

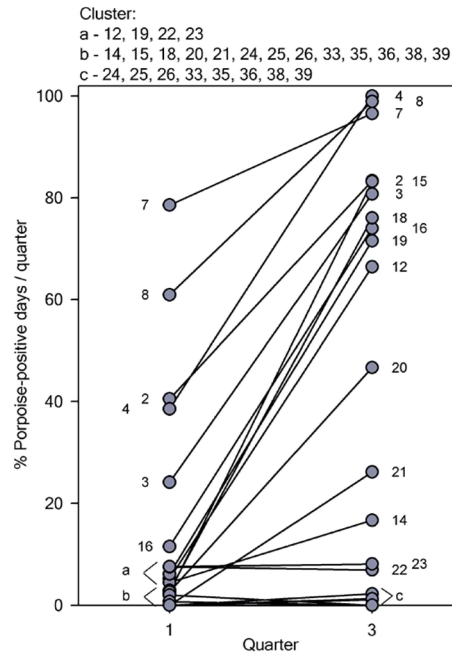


Figure 4. Percentage of porpoise-positive days of 23 measuring positions, each averaged over the years for the first quarters (mainly winter) and third quarters (mainly summer). The numbers next to the symbols give the identifier for the measuring position. The identifiers for the clustered values (a, b, c) are given above the graph.

of particular importance when comparing data gathered with different T-PODs. Therefore, several tests have been conducted to test the comparability of the data gathered for this project.

The change of the settings from ratio 4 to ratio 6 affected neither the sensitivity nor the comparability of the gathered data (Verfuß et al., 2004a). Also, data recorded with version 2 T-PODs were comparable with the data of version 3 T-PODs (Verfuß et al., 2004b), so long as all train classes mentioned in section 'data analysis' (see below) were included in the data analysis.

The sensitivity of the T-PODs was included in the statistical analysis of the first year's data presented and described in Verfuß et al. (2006), so as to reveal any influence of differences in T-POD sensitivity. It could be shown that there was no influence of sensitivity on the results.

Recordings of one T-POD of version 3 and two T-PODs of version 4, set to the same sensitivity, obtained at the same spot within a porpoise-rich area for 4 days showed comparable results when comparing the amount of hours with porpoise detections. During this test, one v4 was set to *noise adaptation*=++ while the other was set to *noise adaptation*=+.

Data analysis

The train detection algorithm (V2.2) has been used to identify click trains within the gathered data. Click trains classified by the algorithm as *high probability cetacean click*

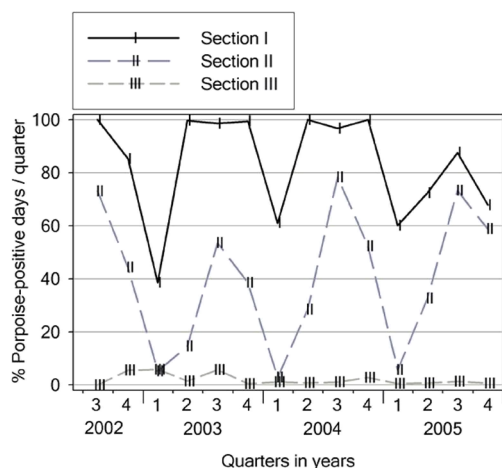


Figure 5. Percentage of porpoise-positive days per quarter for section I, lying west of longitude 11°30'E (solid black line), section II, lying between longitudes 11°30'E and 13°05'E (long dashed dark grey line) and section III, being east of longitude 13°05'E (short dashed light grey line). Please note that from 2005 onwards, the observation area was expanded to the Kiel Bight, probably influencing the results of section I.

trains down to *very doubtful trains* were manually reviewed for harbour porpoise echolocation click trains, as described in Verfuß et al. (2004a,b). Click trains which were manually attributed to porpoise origin, were included in the data set, while those manually attributed to boat noise or background noise were excluded from the data set. For further analysis, porpoise-positive days, defined as a day with at least one classified porpoise click train, were determined from all data recordings. The percentage of porpoise-positive days per monitoring days within a quarter of a year (%PPD/Q) was calculated for each position. A monitoring day is defined as a day in which a T-POD gathered usable data.

Statistics

The resulting %PPD/Qs have been tested for geographical and seasonal differences.

Geographical differences

We tested the null hypothesis that there is no relationship between %PPD/Q and the longitude of the measuring positions: Spearman's rank correlation coefficient was calculated separately for each combination of year and quarter (a total of 14 correlations between the %PPD/Qs and the longitudes of the corresponding measuring positions). The correlation-coefficient was then tested with a sign test to examine the null hypothesis that positive and negative correlation coefficients are equally likely.

P-values were calculated with the permutation method (1000 permutations each). The alpha-level adjustment to correct for multiple testing was conducted using a binomial approach after Cross & Chaffin (1982) as well as Fisher's omnibus test (Haccou & Meelis, 1994).

We also tested the null hypothesis that there is no relationship between the geographical distance of the

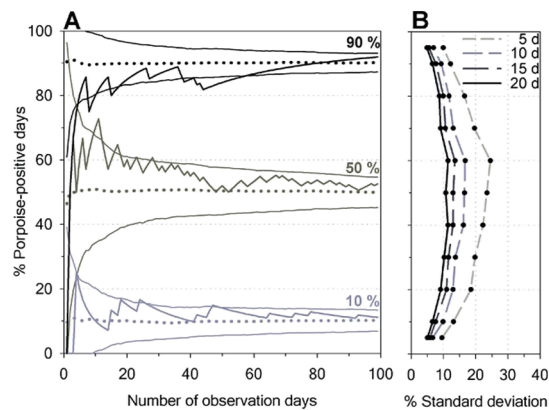


Figure 6. Mean percentage of porpoise-positive days (A, dotted lines) and +/- standard deviation (A, thin lines) from 250 simulations each of a range of numbers of observation days (B, 5 d: light grey short dashed line; 10 d: middle grey middle dashed line; 15 d: dark grey long dashed line, 20 d: black line) and a range of underlying %PPD values (A, 10%: light grey; 50%: grey; 90%: black; B, black dots). Thick (serrated) lines in (A) show one simulation for each sample size.

measuring positions to each other and the comparability of their results: for the quarter with the highest sample size, the third quarter of 2005, a correlation of the geographical distances and differences between the results of the measuring positions was investigated. Therefore, for each pair (1; 2) of measuring positions, the dissimilarity (C_{ij}) of their data was calculated:

$$C_{ij} = \frac{(|\%PPD/Q_1 - \%PPD/Q_2|)}{(\%PPD/Q_1 + \%PPD/Q_2)},$$

if $\%PPD/Q_1 + \%PPD/Q_2 > 0$, otherwise 0.

The relationship between the dissimilarity and the geographical distance of the measuring positions was determined with a matrix correlation. The significance of this correlation was calculated using a Mantel test (Sokal & Rohlf, 1995).

Seasonal variation

We tested the null hypothesis that the results of each measuring position gathered in the first and third quarter respectively, are not different from each other: the means over the years of the %PPD/Qs for the first and the third quarters respectively, were calculated for each measuring position and tested with a Wilcoxon matched-pairs signed-ranks test.

To summarize the outcome of the statistical analysis (see results) in one graph, the study area has been divided into three sections, with *section I* lying west of longitude 11°30'E, *section II* being between longitudes 11°30'E and 13°05'E, and *section III* lying east of 13°05'E (Figure 2). %PPD/Qs have been calculated for each section by summing the porpoise-positive days, as well as the observation days, of all measuring positions lying within the corresponding section, and calculating their quotient.

Table 1. Number of monitoring days and number of measuring positions per quarter (given in brackets) of the monitoring years 2002 to 2005 for section I to III.

Year	Quarter	No. of monitoring days (No. of measuring positions)			
		Section I	Section II	Section III	Total
2002	3.Q	18 (1)	278 (7)	5 (1)	301 (9)
	4.Q	238 (5)	273 (7)	216 (5)	727 (17)
2003	1.Q	70 (1)	114 (5)	326 (4)	510 (10)
	2.Q	312 (4)	239 (4)	344 (4)	895 (12)
	3.Q	218 (4)	218 (7)	218 (4)	821 (15)
	4.Q	190 (3)	440 (6)	235 (5)	865 (14)
2004	1.Q	95 (2)	497 (6)	91 (2)	683 (10)
	2.Q	45 (1)	496 (6)	261 (4)	802 (11)
	3.Q	92 (1)	226 (6)	279 (5)	597 (12)
	4.Q	180 (2)	401 (9)	505 (11)	1,086 (22)
2005	1.Q	133 (4)	141 (5)	389 (10)	663 (19)
	2.Q	525 (9)	851 (11)	985 (18)	2,361 (38)
	3.Q	725 (10)	948 (11)	1,575 (20)	3,248 (41)
	4.Q	669 (10)	821 (10)	1,269 (19)	2,759 (39)
Total		3,510 (10)	6,083 (11)	6,725 (21)	16,318 (42)

No., number.

Influence of the number of monitoring days on the reliability of the results

To evaluate the degree of reliability of the percentage of porpoise-positive days gained in a specific monitoring period, the following simulation has been conducted.

Eleven fixed percentages of porpoise-positive days per hundred monitoring days (5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 95%) have been attributed to a supposed area. Random series of porpoise-positive days and porpoise-negative days (i.e. no detection on that day) that could be obtained in that area were simulated 250 times for each specific outcome. For each of the 250 simulations for the eleven data sets, the percentage of porpoise-positive days was calculated for each number of monitored days from 1 to 100. For each of these numbers of monitored days, the mean and the standard deviation of the 250 calculated percentages of porpoise-positive days was determined for each fixed percentage of porpoise-positive days.

RESULTS

Harbour porpoises have been registered at nearly all measuring positions throughout the German Baltic Sea, except for a very few positions in the Pomeranian Bay (Figure 2). The data show a regular and year-round use of the German Baltic Sea by these animals, but with geographical differences and seasonal variation in the percentage of porpoise-positive days.

Geographical differences

A significant decrease of the %PPD/Q from west to east was seen in nearly all quarters of the different years (Figures 2&3), except for those with a sample size lower than 12 (nearly all $P \leq 0.001$; with rho from -0.756 ($N=19$, 1st quarter 2005)

to -0.966 ($N=14$, 4th quarter 2003), except: 2nd quarter 2004: $P=0.002$; rho= -0.842 ; $N=11$; 3rd quarter 2002: $P=0.071$; rho= -0.627 ; $N=9$; 1st quarter 2003: $P=0.146$; rho= -0.497 ; $N=10$; and 1st quarter 2004: $P=0.338$; rho= -0.328 ; $N=10$; sign test: $P=0.00012$; alpha-correction after Cross & Chaffin (1982): $P < 0.0001$; Fisher's omnibus test: $\chi^2=161.9$; $df=28$; $P < 0.0001$).

The matrix correlation of the geographical distances between the measuring positions and the differences between their data obtained in the third quarter of 2005 revealed a significant correlation (rho= 0.573 , $P=0.001$). This means that neighbouring measuring positions show similar results and data become more dissimilar with increasing distance between positions.

Seasonal differences

Seasonal differences have been revealed for the %PPD/Q (Figure 4). At 23 measuring positions, data were gathered for the first and third quarter. Those data showed a significantly higher percentage of porpoise-positive days in the third quarter (July to September) — which mainly mirrors summer — compared with the first quarter (January to March), largely corresponding to winter time (Wilcoxon test: $z=3.509$; $N=23$ (2 ties); $P < 0.001$).

The %PPD/Qs calculated for the sections I to III clearly mirror the statistically significant seasonal variation and geographical difference in %PPD/Q (Figure 5; Table 1). Figure 5 shows the aggregated data, in which quarters are not strictly comparable e.g. the reduction in the %PPD/Q in 2005 in section I compared to the years 2002 to 2004 might be due to the inclusion of measuring positions in the Kiel Bight from 2005 onwards rather than due to changes in the porpoise population.

Influence of the number of monitoring days on the reliability of the results

The simulation we conducted shows that the reliability of the results depends on the number of monitoring days as well as on the prevailing situation causing a specific percentage of porpoise-positive days: The variability of data gets smaller with increasing number of monitoring days (Figure 6A&B). For a fixed number of monitoring days, the standard deviation rises with rising predetermined values for the percentage of porpoise-positive days up to around 50%, and then decreases again with rising predetermined values (Figure 6B). This fact has been taken into account when deciding on the bin width of the percentage of porpoise-positive days for Figure 2 (largest bin width for middle range percentages, decreasing bin width towards 0% and 100%, respectively).

For monitoring periods with a minimum of 14 monitoring days, the percentage standard deviation resulted in values below $\pm 15\%$.

DISCUSSION

Our data show the importance of the German Baltic Sea as a habitat for harbour porpoises. We found that the species was present in the German Baltic Sea all year round (Figure 2), with decreasing acoustic detections of harbour porpoises from west to east, as well as increasing porpoise detections during the breeding and mating seasons (spring and summer), and a subsequent decrease in winter time (Figures 3–5).

We interpret the changes in the proportion of porpoise-positive days throughout the year and differences across areas as temporal changes and geographical differences in harbour porpoise density. Abundance estimates with visual surveys, showing that the density of harbour porpoises in the German Baltic Sea decreases from west to east (Scheidat et al., 2004a,b; Siebert et al., 2006), confirm our statement, that the percentage of porpoise-positive days reflects the density of harbour porpoises in our study area.

The decrease in the proportion of porpoise-positive days per quarter from west to east has been shown in all observation years. Whereas the decrease is prominent with a large slope in the second to third quarters of the years, the slope of regression for the first quarter is not as steep and is only significant for the first quarter of one year, 2005 (Figure 3), mirroring the seasonal changes then.

In the first year of our study, seasonal changes in the detection rate of harbour porpoises in the German Baltic Sea were already obvious (Figures 2&5) and were confirmed in the subsequent years of static acoustic monitoring. Seasonality is only prominent for measuring positions in sections I and II (Figures 1, 4&5).

One could argue that harbour porpoises, like other cetaceans, might show seasonality in their vocalization, and that a decrease in acoustic detection is more a matter of non-vocalization than of a decrease in the number of porpoises present. The mating song of some baleen whales, e.g. humpback whales (*Megaptera novaeangliae*), is heard during the winter breeding season, but seldom at other times (Gordon & Tyack, 2001). However, in contrast to the echolocation behaviour of harbour porpoises, those vocalizations

do have a communication function. Echolocation is an active sensory system delivering information about the porpoise's environment. Verfuß et al. (2005) demonstrated the importance of echolocation for harbour porpoises. Porpoises, which were living in a well-known, semi-natural outdoor pool, continuously used echolocation, even in easy orientation tasks during daylight, regardless of the season. Differences in the environmental complexity (uncluttered versus cluttered) or in behavioural status (orientation and foraging) only affected the rate of click production, but did not result in an interruption of echolocation. A wild harbour porpoise carrying an acoustic datalogger also used its sonar system almost continuously (Teilmann et al., 2005). Pauses between click trains were logged with a maximum of 222 seconds, but 90% of the silent periods were less than 15 seconds. Therefore, almost continuous use of echolocation by harbour porpoises is very likely.

Until the mid-20th century, a migration of harbour porpoises between the North and Baltic Seas was believed to occur (reviewed in Koschinski, 2002). In spring, the porpoises were thought to have followed movements of herring, passing through Danish waters into the Baltic Sea. In late autumn and winter, when the Baltic tended to freeze over in some years, the porpoises may have migrated back out of the Baltic Sea. Nowadays, the porpoise populations are too small to easily prove such migrations. Teilmann et al. (2004) were able to prove seasonality in the use of areas in Danish waters with the help of satellite tags on porpoises. Siebert et al. (2006) also showed seasonality, in more than ten years' data collection of incidental sightings and strandings in the German Baltic Sea, with a maximum of sightings and strandings in the summer months July to September. The authors discuss the possibility that the data from incidental sightings might be biased by a lower effort in winter (e.g. fewer sailing boats), whereas the strandings data, obtained by a year-round observer scheme and standard procedure ensuring stable monitoring efforts, may be biased by a longer submersion time of carcasses when water temperature is low (Moreno et al., 1993) and because of the unknown drift route that they may take.

Geographical and seasonal changes in environmental conditions might be an argument for explaining geographical and seasonal changes in the T-POD data. Temperature and salinity can affect the speed of sound in water (Richardson et al., 1995), but does not affect the absorption of sound that could influence the detectable range of a porpoise click train. Therefore, the decreasing concentration of salinity prevailing in the Baltic Sea (Janssen et al., 1999) is unlikely to cause the decrease of porpoise registrations from west to east. Variation in temperature and salinity along with water depth, on the other hand, does affect sound propagation (Richardson et al., 1995), as sound bends when travelling through water strata of different temperature and salinity. This effect of refraction can affect the sound intensity over kilometres. However, very high frequencies, as found in porpoise echolocation clicks, do have a high loss of sound density due to absorption, resulting in a short detection range of the clicks. Therefore, refraction cannot affect the clicks' sound intensity over a range of kilometres as it would for low frequency sound.

Furthermore, harbour porpoises are very mobile animals, passing through different water depths (Lucke et al., 2000; Read & Westgate, 1997) during the course of swimming, feeding and breathing. This reduces the risk of an animal being undetectable by a T-POD. For analysing porpoise-positive days, only a short part of a click train must be detected by the T-POD to make a day porpoise-positive. Furthermore, analysis of porpoise-positive days per quarter showed that neighbouring measuring positions obtained similar results and became more dissimilar with growing distance in between the positions. Thermo- and haloclines in the Baltic Sea are very heterogeneous with respect to space and time, especially when passing through different water depths. If this phenomenon did have an influence on the data, neighbouring positions at different water depths would not gather such comparable data.

The number of monitoring days per quarter of each year, as given in Figure 2 and Table 1, has also been sufficient at most of the measuring positions to give representative data, following the results of the model shown in Figure 6. Also the varying and increasing number of measuring positions does not change the replication of seasonal and geographical variation in each of the monitored years.

The measuring positions in section III (east of 13°05'E) did not show any obvious seasonality (Figures 1, 4 & 5). Huguenberger et al. (2002) hypothesized that porpoises inhabiting the waters east of the Darss Sill do not migrate over longer distances to the west in ice free winters. Their morphological studies revealed the existence for a separate sub-population of harbour porpoises in the Baltic proper, i.e., east of Darss Sill. Those data have been confirmed by genetic investigations (Tiedemann, 2001). The low density of this sub-population raises serious concern for the survival of the population, which is especially emphasized in the Recovery Plan for Baltic harbour porpoises (the Jastarnia Plan of ASCOBANS). The T-POD data confirm a very low density of harbour porpoises in the German part of the Baltic proper. Further east and north, in the Swedish and Polish Baltic proper, harbour porpoise encounters become rare (reviewed in Koschinski, 2002). This area is now considered as the north-easterly distribution range of harbour porpoises in the Baltic Sea (Koschinski, 2002). The very low density of the Baltic-proper harbour porpoise makes this sub-population very vulnerable. Any negative anthropogenic influence (e.g., fishery by-catch, chemical or noise pollution) on this very small and therefore highly endangered sub-population might sooner or later lead to its extinction if no action is taken.

The method of T-POD deployment proved to be a very valuable tool for investigating changes in harbour porpoise density within the German Baltic Sea on a temporal and geographical scale. The present study proves a regular use of the German Baltic Sea by harbour porpoises with geographical differences in porpoise density and a seasonal migration pattern of the harbour porpoises inhabiting the German Baltic Sea. The higher numbers of harbour porpoise detections in spring to autumn compared with winter indicate that the German Baltic Sea is an important breeding and mating area for these animals. The infrequent detections of harbour porpoises north and east of the island

of Rügen confirm a very low density of the Baltic-proper harbour porpoise sub-population, and raise an immediate need for protection measures.

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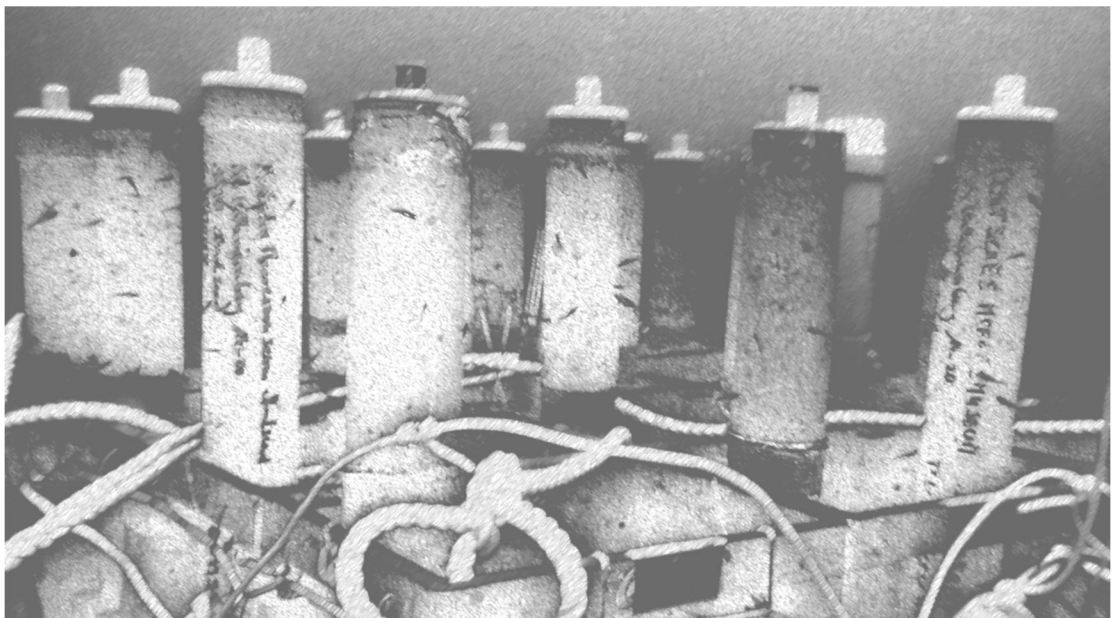
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2 Determining the detection thresholds for harbour porpoise clicks of autonomous data loggers, the Timing Porpoise Detectors

Timing Porpoise Detectors (T-PODs, Chelonia Ltd.) are autonomous passive acoustic devices for monitoring odontocetes. They register the time of occurrence and duration of high frequency pulsed sounds as possible odontocetes echolocation clicks. Because of evolution, five T-POD versions exist. Although the manufacturer replaced those by a digital successor, the C-POD, T-PODs are still used, and data from many field studies exist. Characterizing the acoustic properties of T-PODs enables the interpretation of data obtained with different devices. Here, the detection thresholds of different T-POD versions for harbor porpoise clicks were determined. While thresholds among devices were quite variable in the first T-POD generations, they became more standardized in newer versions. Furthermore, the influence of user-controlled settings on the threshold was investigated. From version 3 on, the detection threshold was found to be easily adjustable with version-dependent setting options “minimum intensity” and “sensitivity,” enabling the presetting of standard thresholds. In version 4, the setting “click bandwidth” had a strong influence on the detection threshold, while “selectivity” in version 3 and “noise adaptation = ON” or “OFF” in version 4 hardly influenced thresholds obtained in the tank tests. Nevertheless, the latter setting may influence thresholds in a complex acoustic environment like the sea.

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T-PODs (and one C-POD) moored for an intracalibration close to the island Omø in Denmark (© Harald Benke/Deutsches Meeresmuseum)

Determining the detection thresholds for harbor porpoise clicks of autonomous data loggers, the Timing Porpoise Detectors^{a)}

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Timing Porpoise Detectors (T-PODs, Chelonia Ltd.) are autonomous passive acoustic devices for monitoring odontocetes. They register the time of occurrence and duration of high frequency pulsed sounds as possible odontocetes echolocation clicks. Because of evolution, five T-POD versions exist. Although the manufacturer replaced those by a digital successor, the C-POD, T-PODs are still used, and data from many field studies exist. Characterizing the acoustic properties of T-PODs enables the interpretation of data obtained with different devices. Here, the detection thresholds of different T-POD versions for harbor porpoise clicks were determined. While thresholds among devices were quite variable in the first T-POD generations, they became more standardized in newer versions. Furthermore, the influence of user-controlled settings on the threshold was investigated. From version 3 on, the detection threshold was found to be easily adjustable with version-dependent setting options “minimum intensity” and “sensitivity,” enabling the presetting of standard thresholds. In version 4, the setting “click bandwidth” had a strong influence on the detection threshold, while “selectivity” in version 3 and “noise adaptation = ON” or “OFF” in version 4 hardly influenced thresholds obtained in the tank tests. Nevertheless, the latter setting may influence thresholds in a complex acoustic environment like the sea. © 2013 Acoustical Society of America. [<http://dx.doi.org/10.1121/1.4816571>]

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I. INTRODUCTION

Timing porpoise detectors (T-PODs, Chelonia Ltd.) are autonomous devices logging the duration and time of occurrence of specific acoustic ultrasound events. T-PODs have proved to be a valuable tool not only for the investigation of the echolocation behavior of harbor porpoises (*Phocoena phocoena*, L. 1758) around fishing nets (e.g., Tregenza, 1998; Carlström *et al.*, 2009), but also for monitoring their presence in areas of interest (e.g., Bailey *et al.*, 2010; Simon *et al.*, 2010). They have been used world-wide. T-PODs were used in long term studies of harbor porpoise presence in the German Baltic Sea (Verfuß *et al.*, 2007, 2008), in environmental impact studies in connection with wind farm construction (Carstensen *et al.*, 2006; Brandt *et al.*, 2011; Scheidat *et al.*, 2011; Teilmann and Carstensen, 2012; Tougaard *et al.*, 2009) and around offshore gas facilities (Todd *et al.*, 2009).

Since market introduction, the T-POD has been continuously improved, leading to the existence of five product versions with more or less pronounced differences in the properties of the acoustic recording system. All five T-POD

versions were used in field studies like those mentioned above. The settings of the T-PODs, which determine the acoustic characteristics of the sound events that will be logged, can be user-defined, and may therefore be different across the various studies. However, even using the same settings and the same T-POD-version (version 3), Kyhn *et al.* (2008) observed differences in the detection threshold of up to 15 dB for simulated harbor porpoise like click sounds.

Although the T-POD is nowadays replaced by its digital successor, the C-POD (Chelonia Ltd., UK), T-PODs are still in use, and years of T-POD data have been accumulated, that has been or will be published. The present paper describes the acoustic characteristics of the different T-POD versions V2 to V5, derived by a calibration procedure in a test tank under controlled conditions. The results can be used to determine how data collected using different T-POD versions or with different settings, can be compared. They furthermore show the importance and benefit of a well defined and properly conducted calibration procedure.

II. MATERIAL AND METHODS

A. T-PODs

T-PODs are self-contained data loggers for cetacean echolocation clicks. They consist of a ca. 85 cm long polypropylene tube with a diameter of around 9 cm, a lid at one end and a hydrophone at the other end. The hydrophone is connected to an amplifier and two bandpass filters (henceforth described as filter A and filter B). Filter A is set to the frequency of interest (e.g., 130 kHz for harbor porpoise echolocation click), and filter B, the reference, is set to a frequency that is absent in the target signal (e.g., 90 kHz for

^{a)}Portions of this work were presented in the proceedings of the workshop “Static Acoustic Monitoring of Cetaceans,” the proceedings of the ASCOBANS/ECS Workshop “Offshore wind farms and marine mammals: Impacts and methodologies for assessing impacts”, and the book “Marine mammals and seabirds in front of offshore wind energy.”

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TABLE I. Standard settings for the version 2 (V2) to version 5 (V5) T-PODs for the calibration as performed in the present investigation. Certain setting options are not applicable (n. a.) in specific T-POD versions. The option "Log only clicks longer than [...] (μsec)" was set to 0.

Setting	V2	V3	V4	V5
Target (A) filter frequency (kHz)	130	130	130	130
Reference (B) filter frequency (kHz)	90	90	92	92
Selectivity (Ratio A/B) (V2+V3)	6	6	5	5
Click bandwidth (V4+V5)				
A-Filter sharpness (Q) (V2)	10	short	n. a.	n. a.
"A" integration period (V3)				
B-Filter sharpness (Q) (V2)	18	long	n. a.	n. a.
"B" integration period (V3)				
Noise adaptation (V4+V5)	n. a.	n. a.	+	+
Minimum intensity (V2+V3)	6	6	12	12
Sensitivity (V4+V5)				
Scan limit on N clicks logged	none	none	none	none

harbor porpoise). The output of the filters goes to a comparator/detector circuitry, microprocessor, and digital memory. The memory stack stores, at a $10 \mu\text{sec}$ resolution, the presence and duration of high frequency click sounds that match specific criteria, which are predetermined with user-defined settings (see Table I). A set of D-cell batteries allows logging for 24 h per day over a period of 8 to 10 weeks. A nice and more detailed description of the T-POD can be found in Kyhn *et al.* (2008) and Kyhn *et al.* (2012).

B. Calibration procedure

1. Set-up

T-PODs were calibrated in a $1.0\text{ m} \times 0.7\text{ m}$ fiber glass tank, filled with fresh water to a water depth of 0.68 m. A calibrated sound transmitter (TC4013, Reson A/S, Denmark) and a receiver (a calibrated reference hydrophone TC4014, Reson A/S, Denmark or a T-POD) were placed in medial water depth at a distance of 0.5 m to each other and centered up relative to the tank sides (Fig. 1). The distance between transmitter, receiver and tank boundaries was chosen to avoid interference of the calibration signal with the echoes arising from surface and tank wall reflections (Fig. 2). A series of harbor porpoise echolocation clicks (Fig. 3, Fig. 4) was used to determine the minimum received sound pressure

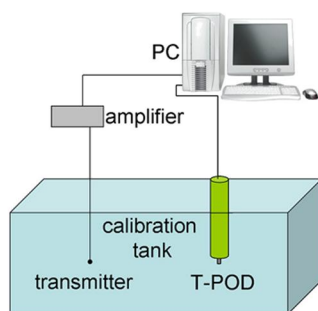


FIG. 1. (Color online) Set-up for calibrating T-PODs. A series of harbor porpoise clicks with decreasing amplitude is generated by a D/A converter controlled by a PC and transmitted via an amplifier through a transducer into a calibration tank. The sound is logged by a T-POD, and subsequently downloaded for analysis by a PC.

level (SPL) at which a T-POD detects and stores the porpoise clicks. This click-series consisted of a total of 26 packages containing ten clicks each with an inter-click-interval of 22 to 31 ms. The amplitude of the ten-clicks-packages was at first reduced by 3 dB (in the second and third package) and then successively by 2 dB (in the fourth to 26th packages), resulting in an overall reduction of the SPL of 52 dB. After the 10th, 15th, 20th and 25th package, a click with high amplitude was inserted to serve as marker for a better counting of the number of recorded packages during analysis. The harbor porpoise echolocation click used to assemble the click-series is shown in Fig. 3. It had a peak frequency (frequency with highest energy in the frequency spectrum) of 136.7 kHz, which is within the normal range of the species (Villadsgaard *et al.*, 2007). Its bandwidths are given in Table II.

The click-series was transmitted through a D/A converter (PCI-6110E, National Instruments, USA) using the software DASyLab (version 7.0, Measurement Computing, USA) via a power amplifier (A1220, T+A, Germany) (which was later on replaced by setting the corresponding amplification in DASyLab), and the TC4013 transmitter. At the beginning of each calibration day, the click-series was picked up by the reference hydrophone, which was connected to one or two

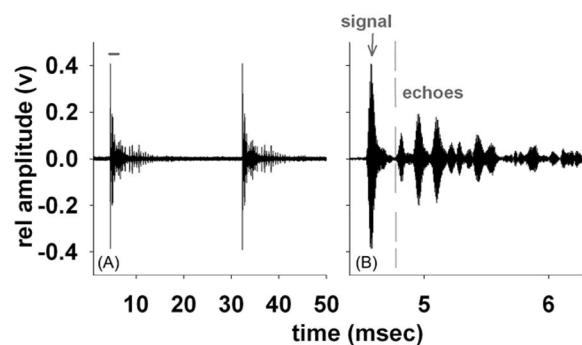


FIG. 2. Recordings of the reference hydrophone: Two test signals (Fig. 3) and their echoes arising in the test tank set-up (Fig. 1). The echoes of a test signal fade out before the next test signal is recorded (A). They arrive at the hydrophone after the end of the test signal (B). (B) is an enlargement of the signal in (A) at the time marked with a gray line in (A).

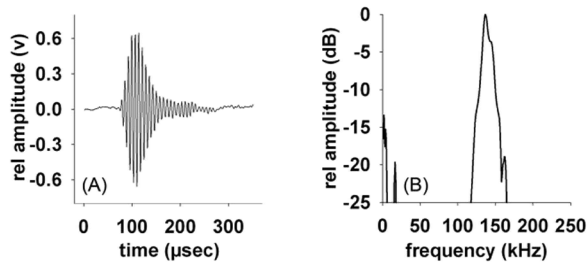


FIG. 3. Amplitude-time signal (A) and power spectrum (B) of the harbor porpoise echolocation click that is used for calibrating T-PODs.

filter/amplifier units (A1101, ETEC, Denmark) and digitized with the PCI-6110E sound card. These calibration recordings were carried out to determine the maximum SPL at the position of the T-PODs. For this, the peak-to-peak (p-p) amplitudes of the first ten-clicks-package containing the highest received SPL were measured using the software Avisoft SASLab Pro (versions 2.2 and 4.52, Avisoft Bioacoustics, Germany) after using the inbuilt “IIR time domain filter” (IIR = infinite impulse response) to high pass filter the sound file at 100 kHz. The transmitted and received click-series was monitored by a digital oscilloscope (TDS-210, Tektronix, USA). After this measurement, the reference hydrophone was replaced by the T-POD to be calibrated. All recordings and transmissions were done with a sampling rate of 1 MHz and a 16 bit resolution. The T-POD calibrations were performed with version-specific standard settings (Table I) if not stated otherwise.

2. Horizontal receiving beam pattern

For the determination of the horizontal receiving beam pattern, the T-POD was rotated in 45° steps around its longitudinal axis after each transmission until the full 360° was completed. This added up to eight horizontal directions measured for each T-POD. At each such direction, and for each test as described below, the click-series was transmitted at least three times, and the mean of the resulting detection thresholds was taken for further analysis.

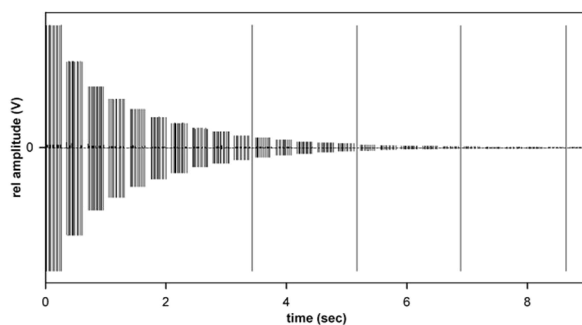


FIG. 4. Amplitude-time signal of the echolocation click series used for calibrating T-PODs. This series consists of 26 packages each containing ten harbor porpoise clicks of the same amplitude. The amplitude decreases by 3 dB (1st to 2nd and 3rd package) and 2 dB (all following packages), spanning over an amplitude range of 52 dB. High amplitude clicks are inserted to separate the 10th, 15th, 20th and 25th package.

TABLE II. Frequency width measured for the -3 dB, -6 dB, -10 dB, and -20 dB bandwidths of the harbor porpoise echolocation click used for the calibration procedure as performed in the present investigation and as shown in Figure 3. Furthermore, the corresponding lower and upper frequency limits are given. Peak frequency of the echolocation click is 136.7 kHz.

Bandwidth (dB)	Frequency width (kHz)	Frequency limit (kHz)	
		Lower limit	Upper limit
-3	7.3	133.8	141.1
-6	15.6	131.8	147.5
-10	21.5	128.9	150.4
-20	37.6	120.1	157.7

For the determination of the detection threshold, i.e., the lowest SPL a T-POD perceives, the number of packages recorded by the T-POD was counted. The detection threshold was calculated as follows:

$$DT_{\text{POD}} = RL_{\text{max}} - 2 \times P, \quad (1)$$

where DT_{POD} is the detection threshold of the T-POD, RL_{max} is the mean received SPL of the clicks of the first package (containing the highest sound pressures transmitted) as measured by the reference hydrophone and P is the mean number of packages recorded by the T-POD for each direction. If the last package recorded did not contain all ten clicks (i.e., not all ten clicks were recorded), only the recorded fraction was added as decimal number (e.g., if the last package recorded was the seventh but contained 5 clicks only it resulted in $P = 6.5$). Formula (1) holds for T-PODs that recorded at least three packages, as the reduction in SPL of subsequent packages from the third package on is 2 dB. Only one very insensitive V2 T-POD recorded less than three packages in some of the tests. For these rare occasions, DT was set to RL_{max} when one package was recorded, and $RL_{\text{max}} - 3$ when two packages were recorded. Otherwise DT was calculated with formula 1.

3. Mean detection threshold and threshold adjustment

The eight detection thresholds determined for the horizontal receiving beam pattern were averaged to obtain a mean detection threshold of the tested T-POD. Since the detection threshold can be adjusted with the setting option “minimum intensity” (V1 to V3, with integers ranging from 0 to 15) and “sensitivity” (V4 and V5, with integers ranging from 1 to 16), the effect of these settings was measured. This was done at the one horizontal direction at which the measured detection threshold value was closest to the mean detection threshold. For each T-POD, the threshold width was determined by subtracting the lowest from the highest detection threshold value obtained for the tested sensitivity/minimum intensity settings. The 10%, 25%, 50%, 75% and 90% percentiles of the threshold width for the different versions were calculated.

Between February 2005 and March 2010, horizontal receiving beam pattern, detection thresholds averaged over the eight horizontal directions, and threshold adjustments

were determined for 121 T-PODs ($9 \times V2$, $49 \times V3$, $47 \times V4$, $16 \times V5$), which were used in field research, e.g., as described in Gallus *et al.* (2012) and Verfuß *et al.* (2007, 2008). Two V1 T-PODs had previously been calibrated in 2005 but were not calibrated with the full procedure and got lost eventually. The results are therefore omitted. Of the V2 to V5 devices, 81 T-PODs have been calibrated multiple times (ranging from two to seven times per unit), with a mean time interval between calibrations of 6 months. The mean values of the repeated calibration results for the detection threshold and the directionality were used for the analysis to ensure that each T-POD was included only once. Changes in the detection threshold over time were analyzed by calculating the difference between the highest and lowest mean detection threshold that was determined for each multiple calibrated T-POD.

4. Testing setting options “selectivity (Ratio A/B),” “click bandwidth,” and “noise adaptation”

Along with the standard calibration as described above, the influence of the setting options “selectivity (Ratio A/B)” in V3 T-PODs, “click bandwidth” in V4, and “noise adaptation” in V4 on the detection sensitivity was tested at random. Therefore, the detection threshold for five V3 T-PODs was determined, each on four horizontal directions (90° steps), for different selectivity values (2, 5, 8, 10, 12, and 14) at three different sensitivity-setting values (1, 6, and 15), the latter setting the T-POD to its highest, a mid-range and lowest detection threshold. The same was done for five V4 T-PODs with different bandwidth values (2, 3, 4, 6, 7, and 8) at three different sensitivity-setting values (1, 6, and 16). (One V4 T-POD recorded self-noise on the most sensitive “sensitivity-setting” of 16 and was then set to 14 instead).

Separate for each direction and sensitivity-setting of a T-POD, the following was done: First, over all the thresholds derived for each “selectivity” or “click bandwidth” value, the detection threshold was averaged. Next, the resulting mean was subtracted from the “selectivity” or “click bandwidth” specific threshold value to determine the influence of the settings

“selectivity” and “click bandwidth” independent from the actual detection threshold of a T-POD. For each “selectivity” and “click bandwidth” value, the mean and standard deviation (s.d.) was calculated, including the results derived for each horizontal direction of each T-POD (i.e., four values per T-POD).

The detection threshold with “noise adaptation = ON” and “OFF,” was determined for five V4 and two V5 T-PODs, each with three different sensitivity-setting values (1, 6, 16). For each sensitivity-setting and each T-POD, the derived detection threshold for “noise adaptation = OFF” was subtracted from the threshold derived for “noise adaptation = ON.”

III. RESULTS

With higher version number, the variation in detection thresholds between T-PODs decreased, and the threshold width was found to be larger (Fig. 5). The mean detection threshold of the tested T-PODs was $125.9 (\pm 8.0 \text{ s.d.})$ dB re $1 \mu\text{Pa}$ (p-p) for V2, $121.2 (\text{s.d.} \pm 3.9)$ dB re $1 \mu\text{Pa}$ (p-p) for V3, $120.2 (\text{s.d.} \pm 1.5)$ dB re $1 \mu\text{Pa}$ (p-p) for V4, and $121.2 (\text{s.d.} \pm 1.9)$ dB re $1 \mu\text{Pa}$ (p-p) for V5 T-PODs (Fig. 6). While the difference in detection threshold between the most and least sensitive T-POD was more than 27 dB for the nine calibrated V2 T-PODs, it was 18.2 dB for V3, 6.5 dB for V4 and 7.9 dB for the V5 T-PODs. The standard deviation of the mean detection threshold over the eight horizontal directions, representing a measure for the directionality of the receiving beam pattern, was 1.6 dB (s.d. ± 1.0) for V2, 1.2 dB (s.d. ± 0.7) for V3, 0.9 dB (s.d. ± 0.6) for V4, and 1.1 dB (s.d. ± 0.6) for the V5 T-PODs (Fig. 6).

The ability to adjust thresholds in V2 T-PODs was small compared to their successors, offering a range of 6.4 dB (s.d. ± 3.6) for V2, 11.5 dB (s.d. ± 2.6) for V3, 21.2 dB (s.d. ± 0.8) for V4, and 21.4 dB (s.d. ± 1.1) for V5 (Fig. 5, Fig. 6).

The least sensitive V2 T-POD (Fig. 5) was calibrated three times. In one calibration, it recorded at one out of the eight directions less than three packages. In all calibrations

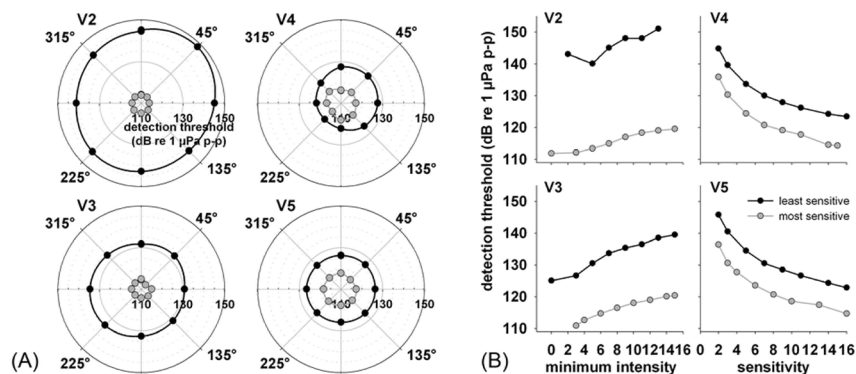


FIG. 5. Horizontal receiving beam pattern (A) and sensitivity curve (B) of version 2 (V2) to version 5 (V5) T-PODs. Shown are the detection thresholds of each version’s least (black line) and most (gray line) sensitive T-POD. Detection thresholds are determined at eight different horizontal directions, in 45° steps (A). The mean detection threshold is derived by averaging the thresholds over the eight directions. At the direction with the threshold closest to this mean threshold, the sensitivity curve (B) for the unit is determined. For obtaining these curves, the detection thresholds for a T-POD set to different “minimum intensity” values (V2, V3) and “sensitivity” values (V4, V5), respectively, were measured. While the difference in thresholds of the least and most sensitive V2 T-POD is around 27 dB, the width of thresholds each can be set via the “minimum intensity” setting to is less than 7 dB. The thresholds get more standardized in higher versions while the adjustable width of each individual POD by changing “minimum intensity” and “sensitivity” values gets larger.

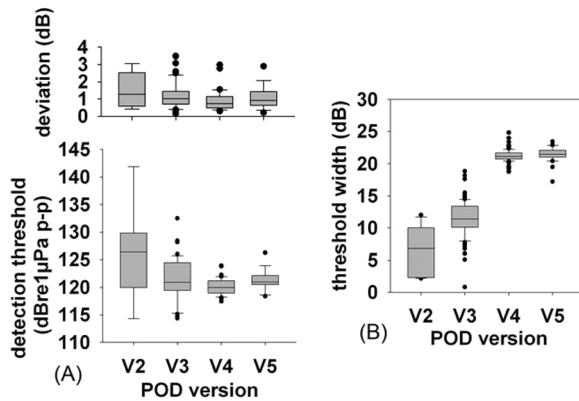


FIG. 6. (A) Mean detection thresholds of all calibrated T-PODs with settings as described in Table I for version 2 (V2) to version 5 (V5), and their standard deviation taken over the eight horizontal directions. (B) The width between minimum and maximum detection threshold, to which the T-PODs could be adjusted to by changing the setting “minimum intensity” (V2, V3) and “sensitivity” (V4, V5), respectively (threshold width). Included are the calibration results of 9 V2, 49 V3, 47 V4, and 16 V5 T-PODs. Shown are the median (black line within gray box), the 25% and 75% percentiles (lower and upper gray box boundaries), the 10% and 90% percentiles (lower and upper whiskers) as well as each value below the 10% and above the 90% percentiles, showing values from the most and least sensitive T-POD (and with the most and least even directionality) (A), as well as the values from the T-PODs with the largest and smallest threshold width (black dots).

with “minimum intensity” settings above eight it recorded three or less packages.

We observed that in 88% of the T-PODs, the change of detection threshold over time was less than 2 dB. The change in detection threshold was less than 0.5 dB for 14% of the T-PODs, and further 33% showed a change of between 0.5 and 1 dB. Also 41% showed detection thresholds between 1 and 2 dB, and 12% had a change in detection threshold of >2 dB, with a maximum of close to 4 dB (Fig. 7).

The setting option “selectivity (ratio A/B)” in V3 T-PODs hardly affected the detection threshold at all in this test tank situation [Fig. 8(A)]. In contrast, in V4 T-PODs, choosing the “click bandwidth” option had a marked influence on the detection threshold: The detection threshold decreased with increasing “click bandwidth” number [Fig. 8(B)]. The maximum threshold difference is approximately

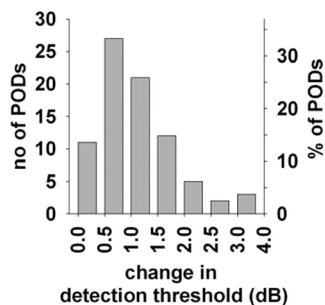


FIG. 7. Change of detection threshold over time. Number of T-PODs with a change in detection threshold of up to 0.5, 1, 1.5, 2, 2.5, 3, and 4 dB in the obtained detection thresholds of repetitive calibrations. T-PODs were calibrated on average every half year.

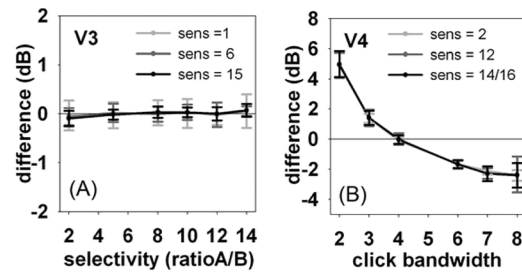


FIG. 8. Influence of the setting option “selectivity” on the detection threshold of T-PODs version V3 (A) and “click bandwidth” on the threshold of V4 T-PODs (B). The graphs show the difference between detection thresholds obtained for each single of the six specific “selectivity” (A) and “click bandwidth” (B) settings and the overall mean obtained by averaging over those six threshold values. This difference is determined for five V3 and five V4 T-PODs, each tested at four horizontal directions (90° apart), and with three different “sensitivity” settings, giving 20 threshold value samples (5 × 4) for each specific “selectivity” and “click bandwidth” setting at three “sensitivity” settings. Shown are the mean difference and its standard deviation over the samples. Positive differences result in a higher detection threshold, and negative differences in a lower detection threshold than the mean threshold of a T-POD.

7 dB between the detection threshold obtained with the lowest and highest setting number. This influence of the “click bandwidth” setting on the detection threshold is independent of the sensitivity setting [Fig. 8(B)].

The “noise adaptation” option, available in V4/V5 T-PODs only, did not have any effect on the detection threshold. All tested T-PODs showed similar results with “noise adaptation = OFF” or “ON,” with a mean difference in thresholds between both calibrations of 0.3 dB (s.d. ± 0.2).

IV. DISCUSSION

The results show that with increasing version number, the T-PODs are more standardized. The variation in the detection thresholds of individual devices was smaller in more recent versions. Still there were differences of several dBs in the detection threshold for harbor porpoise clicks that could result in a big difference between the sizes of the monitored space by two T-PODs with different detection thresholds, as already pointed out by Kyhn *et al.* (2008). The lower the detection threshold, i.e., the more sensitive a T-POD is, the larger is the monitored space, and the higher is the likelihood of logging porpoise clicks. Understanding the acoustic properties of deployed devices enables a better interpretation and comparison of data retrieved by different T-POD devices.

The detection thresholds observed in this study for V3 T-PODs for similar settings as used by Kyhn *et al.* (2008) was in the range of those obtained in their study for ten V3 T-PODs. However, the detection threshold of our least sensitive T-POD is about 9 dB lower than that mentioned by Kyhn *et al.* (2008). Nevertheless, the detection thresholds obtained in both studies are not directly comparable, as Kyhn *et al.* (2008) set a minimum duration of 50 µsec for the click logging, whereas in the present study this was set to 0. If in the present study, clicks shorter than 50 µsec would not have been considered, the detection thresholds would have been higher than reported here. This is due to a correlation

between click duration and its amplitude—with decreasing amplitude the click duration of the logged clicks shortens due to its cosine envelope [Fig. 3(A)].

The receiving beam pattern obtained for the T-PODs in the present study was more (often) radially symmetric in the more recent product versions. The detection threshold is well adjustable from V3 on. This enables the user to adjust single units of the same or different versions to a defined detection threshold to ensure comparable data when monitoring in several locations, like done by Gallus *et al.* (2012) and Verfuß *et al.* (2007, 2008). They chose a certain standard detection threshold to be used on each monitoring location in the German Baltic Sea by adjusting the setting “minimum intensity” or “sensitivity,” respectively, for their V3 to V5 T-PODs.

In most T-PODs the difference in their individual detection thresholds obtained in repeated calibrations was <2 dB, which is in line with the amplitude step size used during calibration. However, some devices showed a considerable shift in their receiving sensitivity, hence affecting data comparability. This observed shift in detection threshold may have been due to a T-POD being exposed to rough conditions during its time at sea, which might have affected its sensitivity. A calibration of each monitoring device in use at least once per year is therefore highly recommended. If a T-POD has been damaged, it should be calibrated after repair. Furthermore, calibration should be undertaken after any lost and found event, as the acoustic properties may have been changed, e.g., if the unit has been washed up on a rocky shore.

The setting option “click bandwidth” had an effect on the detection threshold of V4 T-PODs: higher setting values resulted in a decrease in detection threshold [Fig. 8(B)]. The help-file of the T-POD.exe program states, that high “click bandwidth” values admit sounds of high bandwidth while low values only admit sounds having a lot of energy at the target frequency compared to the reference frequency (Pod.hlp, 2007). While the harbor porpoise echolocation click used in the tests (Fig. 3) is quite narrow band (Table II), the bandwidth may still be larger than the bandwidth admitted by the filter settings. Furthermore, with a peak frequency of 136.7 kHz the click does not quite match the frequency band filter A is set to (130 kHz). With a higher “click bandwidth” setting, a broader frequency range is admitted, and more energy passes the filter, resulting in a higher sensitivity for the transmitted click. The results suggest that this setting has to be considered and corrected for when comparing data derived by T-PODs with different “click bandwidth” settings.

The setting options “selectivity” and “noise adaptation” did not have any effect on the detection threshold of the T-PODs in the present tank calibration. “Selectivity” determines the energy ratio between the outputs from the A and B filters. The energy picked up by filter A has to be to a specific ratio larger than the energy picked up by filter B for the click to be logged by the T-POD. As in the test tank situation no sound around 90 kHz is transmitted or present from elsewhere, it was to expect that changes in this setting option would not affect the sensitivity of the T-POD in the tests. Also in the normal noise spectrum of the sea, the frequency range around 90 kHz is very quiet (Wenz, 1962), whereas it

is present and strong in the spectrum of lower frequency dolphin echolocation clicks (Au, 1993). Therefore this ratio setting is a good tool to discriminate between narrow-band porpoise and broad-band dolphin clicks (Simon *et al.*, 2010).

“Noise adaptation” set to “ON” should reduce the background noise recorded by the T-PODs in the field. As in test tank conditions no background noise was present, it was expected that this option should not have any effect on the detection threshold. Field tests are necessary to gain insights into the comparability of data obtained with and without noise adaptation. For example, in field experiments, Dähne *et al.* (2006) showed that V4 T-PODs recorded more raw clicks when noise adaptation was disabled compared to simultaneously deployed ones with enabled noise adaptation. Nevertheless, the amount of harbor porpoise click trains (being a fraction of the amount of raw clicks), found by a subsequent algorithm, included in the software provided by the T-POD manufacturer, was comparable regardless of the noise setting.

One has to be aware that these test tank calibrations were conducted under controlled conditions with no background noise and one specific echolocation click. Field-tests would give further insights into the value of the test tank calibration, e.g., the simultaneous deployment of different T-POD versions set to the same sensitivity and of the same version set to different sensitivity or different setting options, thus investigating the comparability of the retrieved data.

V. CONCLUSION

Test tank calibration enables the determination the acoustic properties of individual T-POD devices. This knowledge of the acoustic characteristics, especially the detection threshold for harbor porpoise echolocation clicks, will allow a detailed interpretation and comparison of data obtained with different devices. With increasing version number, T-PODs can be regarded as more standardized. From V3 on, the detection threshold can be well adjusted over a large width, which makes it possible to set each individual T-POD to a preselected standard threshold, thereby enhancing the comparability of data collected at different locations.

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3 Use of static passive acoustic monitoring to assess the status of the ‘Critically Endangered’ Baltic harbour porpoise in German waters

Harbour porpoise *Phocoena phocoena* abundance in the Baltic Proper (BP) is at a level where measures for improving the status of this genetically and morphologically discrete population are urgently needed. Without knowledge on seasonal and geographical distribution, a common basis for conservation efforts has been lacking for the past decades. We deployed 22 porpoise detectors from March 2005 until August 2007 in the eastern German Baltic Sea to study seasonal migrations and abiotic factors associated with porpoise presence/absence patterns. Two years of continuous monitoring resulted in 11 890 recording days from 21 stations within the BP, with only 207 porpoise-positive days (ppd—a day with verified porpoise detection), equaling 1.86% ppd per month and station over the study period. Data were analysed using generalised additive models to find significantly influencing factors. Detection rates in the BP peaked twice seasonally: once associated with the summer occurrence of animals from the population living mostly in the Belt Sea and once correlated with (1) cold air temperatures and (2) air temperatures lower than water surface temperatures. The latter suggests that porpoises from the BP migrate towards mostly ice-free waters in winter to avoid suffocation. In order to reduce harmful set-netting, conservation measures must be seasonally regulated, at least, or less harmful fishing methods must be implemented. These findings should help to improve the current European anti-by-catch legislation, e.g. regulation EC 812/2004, which is currently under review.

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A T-POD deployed in the Baltic Sea (© Thomas Förster/Deutsches Meeresmuseum)



Use of static passive acoustic monitoring to assess the status of the 'Critically Endangered' Baltic harbour porpoise in German waters

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ABSTRACT: Harbour porpoise *Phocoena phocoena* abundance in the Baltic Proper (BP) is at a level where measures for improving the status of this genetically and morphologically discrete population are urgently needed. Without knowledge on seasonal and geographical distribution, a common basis for conservation efforts has been lacking for the past decades. We deployed 22 porpoise detectors from March 2005 until August 2007 in the eastern German Baltic Sea to study seasonal migrations and abiotic factors associated with porpoise presence/absence patterns. Two years of continuous monitoring resulted in 11 890 recording days from 21 stations within the BP, with only 207 porpoise-positive days (ppd—a day with verified porpoise detection), equaling 1.86% ppd per month and station over the study period. Data were analysed using generalised additive models to find significantly influencing factors. Detection rates in the BP peaked twice seasonally: once associated with the summer occurrence of animals from the population living mostly in the Belt Sea and once correlated with (1) cold air temperatures and (2) air temperatures lower than water surface temperatures. The latter suggests that porpoises from the BP migrate towards mostly ice-free waters in winter to avoid suffocation. In order to reduce harmful set-netting, conservation measures must be seasonally regulated, at least, or less harmful fishing methods must be implemented. These findings should help to improve the current European anti-by-catch legislation, e.g. regulation EC 812/2004, which is currently under review.

KEY WORDS: *Phocoena phocoena* · Temporal and spatial distribution · Baltic Sea · Generalized additive modelling · Click detector · T-POD

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INTRODUCTION

Harbour porpoises *Phocoena phocoena* are the only cetacean species regularly occurring and reproducing in the Baltic Sea (Scheidat et al. 2008). Porpoises are protected under European legislation,

in particular, by being listed in Annex II and IV of the EU Habitats Directive (92/43/EEC; European Union 1992). These listings require the creation of special areas of conservation (Art. 6) and the establishment of a system of strict protection for the animal species listed (Art. 12) to maintain or allow

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them to recover sufficiently to reach a favourable conservation status. Additional obligations for porpoise conservation in the Baltic Sea arise from intergovernmental agreements and their porpoise recovery goals, such as the 'Jastarnia Plan' of the Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS 2009) and HELCOM Recommendation 17/2 of the Helsinki Convention (Helsinki Commission 1996). Early last century, harbour porpoises occurred within the Baltic Proper (BP), east of the Darß and Limhamn Sill and adjacent waters (Fig. 1), in fairly high numbers, as indicated by strandings (Skóra et al. 1988), by-catch in fisheries (Skóra & Kuklik 2003) and direct catch (Kinze 1995). Since the population has declined (reviewed in Koschinski 2001), special measures are needed to protect this apex predator in a fragile ecosystem.

The causes for the decline of harbour porpoises in the BP are still poorly understood. Possible factors include habitat deterioration due to eutrophication, prey depletion due to over-fishing, severe winters with freezing of large parts of the BP (Seinä & Palosuo 1996) and subsequent die-offs (Koschinski 2001), pollution with chemical toxins such as polychlorinated biphenyls and heavy metals, ship traffic (Koschinski 2001, Jastarnia Group & Bräger 2009) and—probably most important—non-target by-catch in

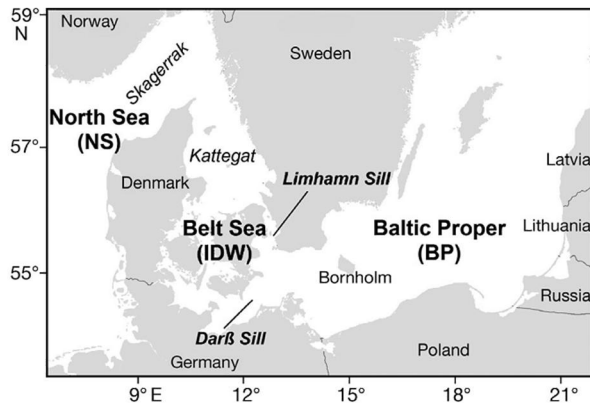


Fig. 1. Overview of the Baltic Sea, excluding the Gulf of Botnia, Finland and Riga. IDW: inner Danish waters

bottom-set gill nets and drift nets (Berggren et al. 2002, ASCOBANS 2009). The European Commission attempted to regulate by-catch of small cetaceans in gill nets (EU Council 2004) by making mandatory (1) the use of acoustic deterring devices (such as pingers) to prevent by-catch in gill nets, (2) dedicated observers to report cetacean by-catch in specified European waters and (3) banning drift nets. Most of the Belt Sea and almost all of the BP, except for ICES (International Council for the Exploration of the Sea) Area 24, however, were excluded from such measures (1 and 2). The use of pingers may not solve the problem in low-density areas (Carlström et al. 2009), because even very low by-catch rates will prevent recovery of Baltic harbour porpoises (Berggren et al. 2002). Construction noise and anthropogenic noise in general probably add a further threat (e.g. Carstensen et al. 2006).

According to genetic and morphological research, 3 distinct populations of harbour porpoises inhabit the Baltic Sea (Figs. 1 & 2) and adjacent areas: (1) the North Sea (NS) population covering also the Skagerrak and the northern part of the Kattegat, (2) the inner Danish waters (IDW) population in the Kattegat and Belt Seas bordered by the Darß and Limhamn Sills and (3) the BP population around the island of Rügen and northwards to Finland (Berggren et al. 1999, Galatius et al. 2011, Huggenberger et al. 2002, Koschinski 2001, Teilmann et al. 2008, 2011, Wiemann et al. 2010).

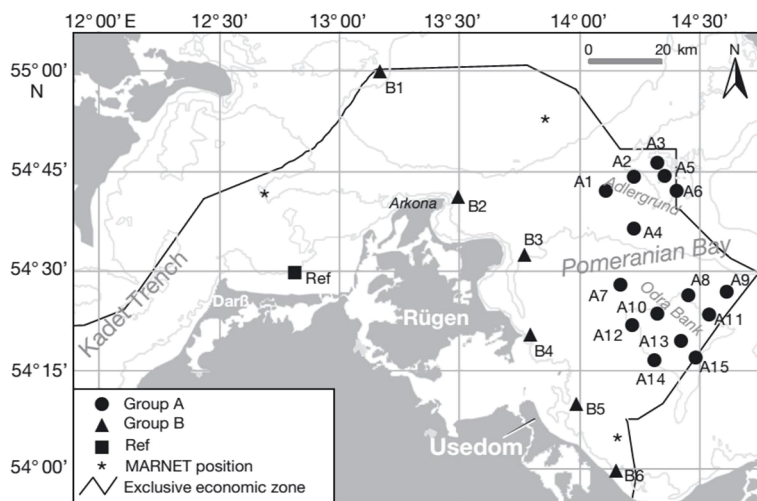


Fig. 2. Positions of click detectors (timing-porpoise-detectors, T-PODs) and MARNET measuring platforms (of the German Maritime and Hydrographic Agency) within the study area. Most co-variables were measured at MARNET positions and applied to the nearest T-POD position. There are 2 extensively shallow areas within Pomeranian Bay: the rocky Adlergrund and sandy Odra Bank

While the population in the North Sea appears to have shifted its distribution south between July 1994 and July 2005 according to the 2 SCANS (Small Cetaceans in the [European] Atlantic and North Sea) surveys (Hammond et al. 2002, SCANS II 2008), the basin-wide abundance has not significantly changed. Healthy status is unlikely, however, for the IDW population (Teilmann et al. 2011) and is most definitely not the case for the BP population. Aerial line transect survey data were collected in an area extending from the south coast of Sweden to Poland and the island of Rügen (Berggren et al. 2002, 2004, L. Hiby & P. Lovell unpubl. data) in the summers of 1995 and 2002. In 1995, a total of 3 porpoises were sighted, and in 2002 a total of 2 observations of porpoise pods were collected off the south coast of Sweden. From these very few observed animals it was estimated using distance sampling, that 599 porpoises (95% CL = 200 to 3300) inhabited this area in 1995 and approximately 93 groups in 2002 (95% CL = 10 to 460). Harbour porpoise in the Baltic are usually observed in group sizes between 1 and 2 individuals (e.g. Berggren et al. 2002, Scheidat et al. 2008). The 2002 result is not significantly lower than in 1995, because the confidence bands are very large due to the extremely small sample sizes.

These low abundance estimates, detection rates and high uncertainty caused serious concern about the population status of harbour porpoises in the BP area. Uncertainty is so high that even the survival of this population has been in question at times. Boat-based surveys with passive acoustic methods as well as visual observers were carried out using a towed hydrophone system in 2001 and 2002 (Gillespie et al. 2005). Only 3 acoustic detections were recorded in the western BP (excluding Polish waters) in 2002, and only 1 visual sighting was obtained on effort in Polish waters in 2001. These surveys confirmed the 'Critically Endangered' status of the BP harbour porpoise population as stated by the IUCN Red list (Hammond et al. 2008).

The border between the 2 populations (IDW and BP) was originally assumed to be the salt water inflow barriers into the BP: the Limhamn Sill in the Øresund and the Darß Sill in the Kadet Trench (Huggenberger et al. 2002, Palme et al. 2004). Teilmann et al. (2011) found that some satellite-tagged porpoise in IDW moved east of the island of Rügen even towards Bornholm. They also found that a small proportion of porpoises from the NS and IDW populations briefly resided within the neighbouring population's area, suggesting that some overlap in distributional range may exist. The Baltic Sea is one of the

largest brackish water bodies of the world and is prone to freezing in severe winters, which may constitute 11% of all winters (Seinä & Palosuo 1996). Ice conditions vary with a salinity gradient from the south-westerly waters of the Belt Sea, dominated by porous ice, up to the north-easterly waters around Finland, Sweden, Russia, Estonia and Latvia, dominated by fast freshwater ice (Granskog et al. 2006).

Harbour porpoises are extremely mobile animals and can travel up to 50 km d⁻¹ (Westgate et al. 1995) and swim approximately 7 km h⁻¹ (Schulze 1996). Maximum speeds are probably between 16.6 km h⁻¹ (Kanwisher & Sundnes 1965) and 22.2 km h⁻¹ (Gaskin et al. 1974), but are unlikely to be sustained over long periods of time.

The use of echolocation click loggers in low-density areas has provided new research opportunities for species such as the vaquita *Phocoena sinu* (Rojas-Bracho et al. 2006, Jaramillo-Legorreta et al. 2007), the Hector's dolphin *Cephalorhynchus hectori* (Rayment et al. 2009), as well as its highly endangered sub-species, the Maui dolphin *C. hectori maui* (Rayment et al. 2011). Since 2002, the German Oceanographic Museum has been carrying out static acoustic monitoring (SAM) of harbour porpoises using click detectors called T-PODs (timing-porpoise-detectors, Chelonia Ltd.) to record the occurrence of these animals continuously within the framework of various research projects (Verfuß et al. 2007, 2008a). Results from these studies suggested strong geographical and seasonal variation in habitat use in the German Baltic Sea west of the island of Rügen. Acoustic detections declined from west to east, increased during spring to peak in summer and declined again in fall. Verfuß et al. (2007) did not show any seasonal variation north and east of the island of Rügen (Pomeranian Bay), the area most probably inhabited by the BP population. Already in 2002, the first version of the Jastarnia Plan of ASCO-BANS (2009) outlined the need for more detailed knowledge on the habitat use of the Baltic harbour porpoise.

We conducted large-scale acoustic monitoring with 22 measuring positions to obtain new information on distribution, seasonal and geographic variation, and ecological dependencies of the BP population in German waters. One major aim of the present study was to find possibilities to protect BP porpoises with regard to their geographical and seasonal distribution, a possible habitat partitioning between BP and IDW populations, and to determine whether SAM is an appropriate tool for monitoring this low-density population.

MATERIALS AND METHODS

T-PODs are self-contained acoustic data-loggers developed to register echolocation clicks of odontocetes via a hydrophone, filters, a sound processor and battery in a watertight housing tested for up to 150 m water depth. The T-POD compares the energy content of the porpoise echolocation frequency band, which typically lies around 130 kHz (Au et al. 1999, Kamminga et al. 1999), and a reference band around 90 kHz, in real-time. Time of occurrence and duration of possible echolocation clicks are saved to a memory chip. Durations registered are highly correlated with the loudness of the signal and can be regarded as a proxy for amplitude. T-POD detection ranges are smaller than 500 m. Calibration of the T-PODs (Dähne et al. 2006, Verfuß et al. 2008b) was conducted before and after the study and once every year to obtain a measure for the variation of instrument sensitivity probably resulting in differences in the amount of recorded clicks. T-POD (Versions 2 to 5) instrument settings are described in Table 1. 'Minimum intensity/sensitivity' was adjusted for individual T-PODs to standardise the detection threshold to 127 dB re 1 μ Pa peak-peak. As not all T-PODs could be set to this value, detection threshold and hardware version were also included as co-variables in the modelling process. Furthermore T-PODs were rotated among deployment locations.

Data were downloaded, processed and exported with the proprietary software 'T-POD.exe' Version 7.4

Table 1. Instrument settings used during the study; minimum intensity/sensitivity setting was adjusted for each instrument's detection threshold. Versions 2 and 3 (V2 & V3) have similar settings; settings for Versions 4 and 5 (V4 & V5) are different due to adaptation of the hardware by the manufacturer; hence, not all settings are applicable to each version. ++: noise adaption switched on. A and B areas, see Fig. 2

Setting	Applicable for	T-POD version	
		V2 & V3	V4 & V5
Target (A) filter frequency	V2–V5	130 kHz	132 kHz
Reference (B) filter frequency	V2–V5	90 kHz	90 kHz
Selectivity (ratio A/B)	V2,V3	6	
Click bandwidth	V4,V5		4
'A' integration period	V2,V3	Short (10)	
'B' integration period	V2,V3	Long (18)	
Noise adaptation	V4,V5		++
Minimum intensity/sensitivity	V2–V5	Variable	Variable
Scan limit of no. of clicks logged	V2–V5	240	240

using train detection algorithm Version 3.0. Train detection of likely harbour porpoise vocalisations in all detection classes ('CetHi' to 'very doubtful') was used to find possible click trains within any given 10 min period. These detections were double-checked visually by trained observers for the presence of harbour porpoise *Phocoena phocoena* echolocation click sequences and then classified as porpoise, boat, or other sound. The minimum number of automatically classified clicks to be regarded as porpoise was defined to be 5. The progression of inter-click intervals (ICI) and duration of individual clicks was used for visual classification taking all registered clicks in that time period into account. Automatic detections of possible porpoise origin were rejected (false positives) when (1) ICI did not show a variation in click pattern typical for echolocation click trains (see Amundin 1991, Au 1993, Verfuß et al. 2005, 2009), e.g. an ICI variation in consecutive clicks of up to $\pm 40\%$; (2) duration was constantly or mostly < 20 or > 500 μ s; and (3) another source of the automatically detected sounds could be identified (boat engine or sonar, ambient noise) as the likely source of the classified clicks. Only verified click sequences were included in all subsequent analyses. From these detections, the proportion of porpoise positive days (ppd) and porpoise positive hours (pph), defined as the percentage of days and hours with at least 1 porpoise detection, was calculated for each month. These fairly coarse time periods were used to reduce the number of zeros for this low-density dataset, to reduce effects of temporal and spatial autocorrelation and to have no or only small impacts from variations in instrument sensitivity and hardware version.

Geographic distribution and seasonal variation

A total of 21 recording positions were chosen for deployment: of these, 15 were placed with even spacing in the 2 extensive shallow-water areas Adlergrund and Odra Bank (marked 'A' in Fig. 2; water depth: 7 to 26 m) under the restrictions of the water and shipping authorities for the Pomeranian Bay. In addition, 5 coastal positions were located between the Arkona cliffs and the Usedom peninsula and another one north of Rügen (marked with 'B' in Fig. 2; water depth: 10 to 22 m). Finally, 1 position north of the Darß peninsula (marked 'Ref' in Fig. 2; water depth: 11 m) was used as a proxy for the occurrence of animals from the IDW population (Verfuß et al. 2007, 2008a). The positioning was consistent with that used by Verfuß et al. (2007), and instruments were deployed approximately 5 to 7 m below the

water surface with small cement anchors (~30 kg) and nylon ropes (diameter: 12 to 14 mm) attached to surface markers (diameter: 20 to 40 cm). The deployment method is described in more detail in Verfuß et al. (2007, 2008a). For habitat modelling, data from stations (Stns) of Groups A and B were used together. To investigate the hypothesis that IDW animals enter the BP and may mask ecological preferences of BP porpoises, a second model was built from Group A data only. Data were collected from March 2005 to August 2007 (Fig. 3). In February 2006, the devices had to be removed for up to 4 wk to avoid equipment loss during strong formation of ice floes.

Environmental data were derived from 3 MARNET measuring platforms of the German Maritime and Hydrographic Agency, which are located within the study area (Fig. 2; www.bsh.de/en/The_BSH/Organisation/BSH_at_a_glance/BSH-Flyer.pdf) to monitor water and air temperatures, salinities, weather conditions and other abiotic factors continuously at different water depths.

Paired detections and diel patterns were analysed for Group A positions only to prevent the possible influence or even masking by IDW animals.

Minimum number of groups indicated by paired detections

Due to the status of the BP population as 'Critically Endangered' (Hammond et al. 2008), it is very important to know whether it is possible that multiple groups of animals use the area at the same time. Finding multiple groups of animals simultaneously in this area would indicate high importance of the area at particular times of the year. If porpoises from the BP move into the area with multiple groups, conservation measures should be taken. For this reason, we tested whether paired detections, i.e. porpoise detections at multiple stations within a period of <8 h, could originate from the same animal/group. Within 8 h porpoises can travel around 56 km while maintaining a swimming speed of 7 km h⁻¹. For comparison, the largest distance between T-PODs in the study area was 55 km. The delay between 2 paired detections (Δt) was calculated as the time difference between the last positive 10 min section detection on one T-POD and the first on another detector. Using the distance between the 2 positions (Δs), a hypothetical minimum swimming speed (v) was calculated.

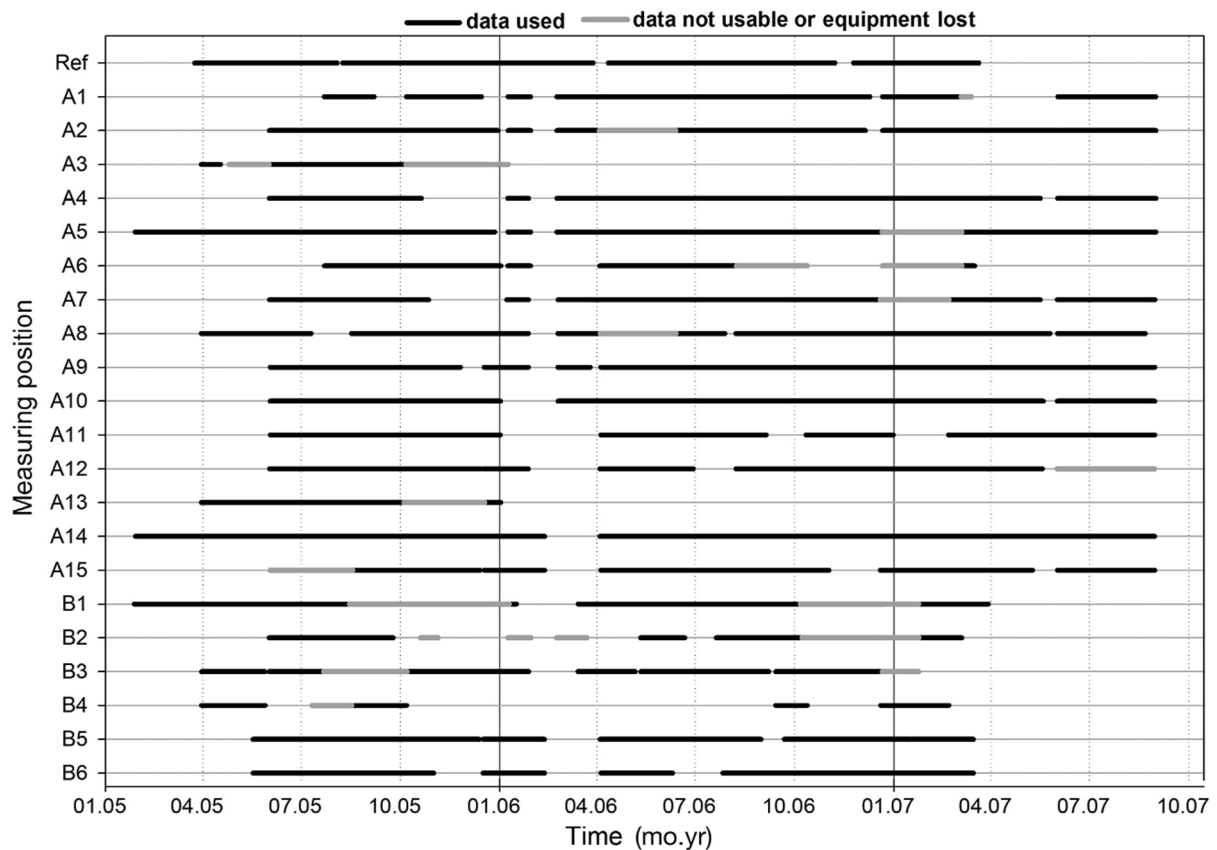


Fig. 3. T-POD deployment period. Site positions as given in Fig. 2

Paired detections were classified by the resulting swimming speeds as follows: 0 to 7 km h⁻¹: possibly from the same animal/group; 7 to 10 km h⁻¹: likely 2 groups, if the swimming speed was maintained for >90 min (i.e. the involved stations were >10.5 km apart); 10 to 22 km h⁻¹: likely 2 different animals/groups, if the time difference was >45 min (i.e. the stations were 8 to 17 km apart); >22 km h⁻¹: definitely 2 different animals/groups. If more than 2 positions had paired detections (according to these criteria), then all speeds between the positions were calculated in the same fashion.

The number of paired detections might also be used as a metric to be considered for a future abundance estimate. As statistics need to be developed for this metric in order to be used in this fashion, we want to show here that they can support species conservation within very low-density areas, where an abundance estimate using regular statistical methods might not be feasible.

Diel pattern

Two daily periods were defined. 'Daytime' was the time between sunrise and sunset, and 'nighttime' was defined as the time between sunset and sunrise. The proportion of 'pph' was calculated per daily period and station, and a test was carried out using a

pairwise comparison (pph_{nighttime} vs. pph_{daytime}) in a generalised linear mixed model with day as a random factor under a quasi-binomial distribution.

Habitat modelling

To determine the influence of abiotic co-variables and to detect seasonal patterns in harbour porpoise distribution in the Pomeranian Bay, generalised additive models (GAM) were built (Hastie & Tibshirani 1990, Wood 2006). Following a similar modelling approach of Gilles et al. (2011) with aerial density estimates, we modelled the influence of co-variables on the dependent variable pph per month. Variables were averaged for each month and applied to the nearest neighbouring T-POD position (Table 2).

Because of possible multicollinearity between parameters, the package HH (Heiberger 2012) with the function VIF (variance inflation factor) was used to find possible correlations and exclude variables prior to model-specific selection. Co-variables were excluded when values for the variance inflation factor exceeded 10 (Belsley et al. 1980). When a decision had to be made between 2 correlated variables to be used for further modelling, the co-variable leading to a higher explained deviance and lower GCV (general cross validation) score was preferred.

Table 2. Variables used for habitat modelling. PSU: practical salinity unit; IDW: inner Danish waters; –: not applicable; PS: present study

Variable	Measured in/on	Abbreviation	Extra information	Unit	Type	Source
Temperature	Air	AT	–	°C	Cubic spline	MARNET
	Surface water	SWT	Sensors at <10 m water depth	°C	Cubic spline	MARNET
	Bottom water	BWT	Sensors at >20 m water depth	°C	Cubic spline	MARNET
	Difference between air and surface water	D-AT-SWT	–	°C	Cubic spline	MARNET
Salinity	Surface	SS	–	PSU	Cubic spline	MARNET
	Bottom	BS	PSU, derived from impedance measurements	PSU	Cubic spline	MARNET
Water depth		WD	–	m	Cubic spline	PS
Latitude and longitude		teLatLong	–	Degrees	Tensor product Wood (2004)	PS
Detection threshold	Test tank calibration for each T-POD every 6–12 mo	DT	–	–	Cubic spline	PS
Hardware version of T-PODs		HV	–	–	Factor	PS
Month		Month	–	–	Cyclic spline	PS
Year		Year	–	–	Cubic spline	PS
Porpoise positive days	At the station 'Ref'	Ref-ppd	Used as a reference for the seasonality of the neighbouring IDW population in German waters (Verfuß et al. 2007, 2008a)	–	Cubic spline	PS

Calculations were carried out using R 2.14.1 (R Development Core Team 2012) and the package *mgcv* 1.7.13 (Wood 2004) assuming a quasi-Poisson distribution, as it can cope with zero inflated values (Zuur et al. 2009). To find the most appropriate model, we used backward selection of significant covariables tested via an ANOVA. Models with significantly lower residual deviance were preferred, as well as models with fewer variables and non-significant differences to the model with more variables. After model selection 10-fold cross validation was carried out to estimate the root mean square error of the prediction (RMSEP; Hastie et al. 2009).

The importance of variables was estimated using the *F*-value. Spatial and temporal autocorrelation was assessed using jittered variograms and autocorrelation function plots of the model residuals in R 2.14.1 and the package *geoR* 1.7.2 (Paulo et al. 2001, Diggle & Ribeiro 2007) for spatial autocorrelation. No autocorrelation patterns were apparent, probably due to the coarse time period (month) used. Data with <5 recording days per month and position were excluded to prevent a bias due to differences in effort.

RESULTS

Between March 2005 and August 2007, recordings of *Phocoena phocoena* were made at all 21 stations in the Pomeranian Bay for a total of 11 890 d (9282 d for Group A only). Of these, porpoise echolocation click trains were recorded on 207 d (Group A: 132 d), resulting in an overall mean of 1.86% ppd per station and month (Group A: 1.48%). For comparison, Stn REF had a mean of 34.02% ppd per month, ranging from 0 to 83.3% during 694 d of operation.

Geographic distribution and seasonal variation

Porpoises were registered at every recording position, except A3 and A13, which had only limited logging time (Fig. 3). With the exception of April and May 2007, porpoises were registered every month. Detections peaked at 19.4% ppd at Stn A7 in July 2007 and 25.8% ppd at Stn B2 in August 2006. Maximum average values per station and month for the entire German part of the Pomeranian Bay were obtained in January 2006 with 5.4% ppd (Group A) and 5.2% ppd in March 2006 for Group AB.

The seasonal pattern of Group AB positions shows only little variation, but points towards a bimodal distribution of ppd with maxima in the winter (January

to March) and again in the summer months (June to August; Fig. 4A). For Group A the variation is even smaller, and the summer peaks are weaker for 2005 and 2006 (Fig. 4B,D). Plotting the ppd per month for the reference position versus surface water temperature (Ref-ppd vs. SWT; Table 2) shows a tight correlation between the variables; Ref-ppd mostly follows the temperatures with a short delay (Fig. 4C). Thus, Ref-ppd appears to follow the same seasonal pattern as the western part of the German Baltic Sea, indicating it to be part of the distribution range of the IDW population (Verfuß et al. 2007). Peak detection rates for Ref-ppd were reached in September 2006, with 83%, and lowest rates occurred generally in winter, with 0 to 7%.

Plotting the mean ppd values of the instrument Groups A and AB (Fig. 4D) shows that a winter peak can be seen in both groups, but that the summer peak is weaker for Group A.

Minimum number of groups indicated by paired detections

A total of 30 paired detections were observed in the dataset. Ten detections could have originated from the same group, as travel speeds were <7 km h⁻¹. Thirteen pairs of detections were classified to have originated from 2 separate individuals or groups (Table 3). In 2 cases it could even be shown that 3 different porpoise groups were registered. Distances between paired detection varied from 8.5 to 51.8 km within a time span ranging from 0 min (simultaneous detection) to 5 h 50 min, requiring hypothetical minimum swimming speeds to get from one position to the other ranging from 7.3 up to 37.5 km h⁻¹. Most of the paired detections were identified in the winter of 2005/2006 and in the summer of 2007.

Diel pattern

There was no detectable diurnal pattern between 'nighttime' and 'daytime' vocalisations during the monitoring period ($p = 0.264$) for Group A (Fig. 5).

Habitat modelling

The variables surface water temperature and bottom water temperature were excluded due to a high VIF in correlation with air temperature. As it appeared counter-intuitive that air temperature should

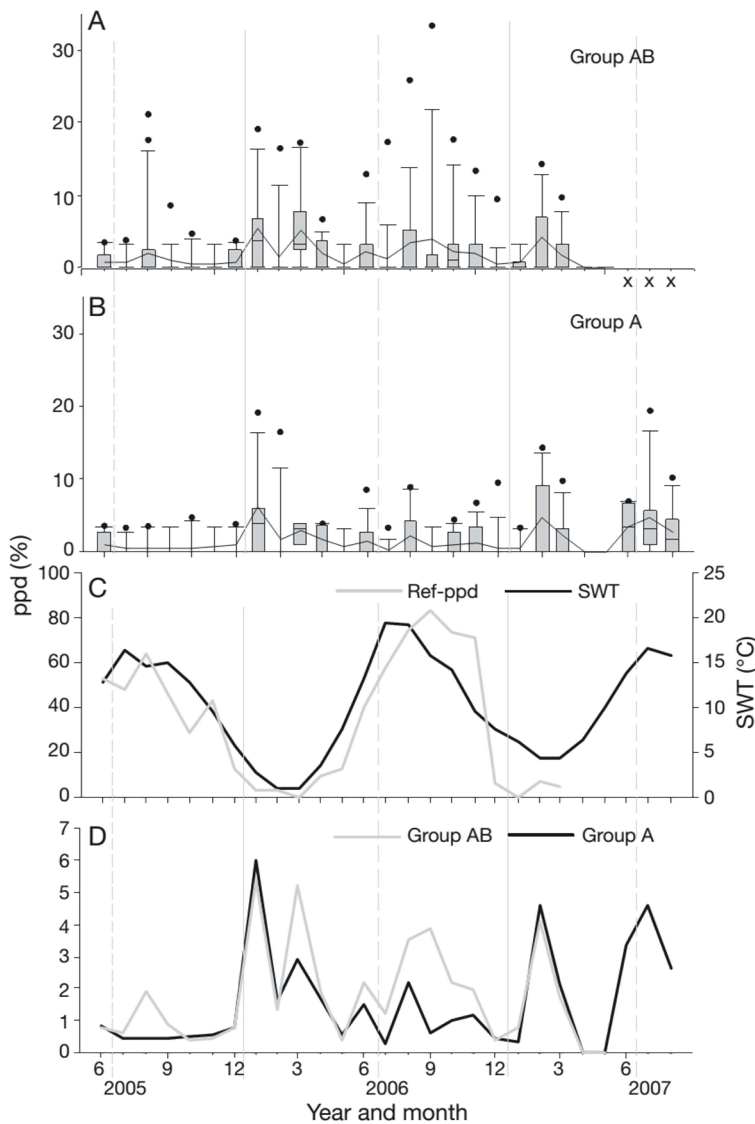


Fig. 4. *Phocoena phocoena*. Percentage of porpoise positive days (ppd) per month (A) for all stations in Group AB (boxplot shows median, quartiles, 90th and 10th percentiles and outliers) and as a mean (black line) and (B) for all stations in Group A. (C) Average ppd per month at Stn 'Ref' (grey line) and surface water temperature (SWT) at the closest MARNET measuring platform (black line); and (D) comparison of mean ppd per month for Groups A and AB

have a stronger influence on porpoise detections than water temperatures, we tested all model selections with both variables, and air temperature led consistently to a higher explained deviance and lower GCV score. Consequently, only results with air temperature are presented here. Cross validation showed that both models significantly underestimate the influences of co-variables due to the large num-

ber of zeros when comparing the difference between model prediction and observed data.

Environmental relationships for all stations north-east of Rügen (Group AB)

The GAM built with Group AB data showed that water depth, hardware version, month, detection threshold and year were not significant co-variables and were thus excluded during backward selection.

The most important factor in the model (Fig. 6) was the ppd at Ref (Ref-ppd; $F = 22.222$, $p = 3.36 \times 10^{-6}$) followed by air temperature ($F = 12.882$, $p \leq 5.62 \times 10^{-8}$), surface salinity ($F = 7.851$, $p = 6.64 \times 10^{-4}$), bottom salinity ($F = 6.483$, $p = 1.13 \times 10^{-2}$), the tensor product of latitude and longitude (teLatLong; $F = 6.108$, $p = 3.29 \times 10^{-9}$) and the difference between air and water surface temperature ($F = 4.137$, $p = 6.64e \times 10^{-3}$). The model explained 41% of the deviance ($R^2 = 0.37$, $n = 419$, RMSEP = 3.64).

The model outcome was heavily influenced by Ref-ppd, showing a positive linear correlation. Air temperature shows a positive influence below 4°C and is insignificant otherwise, except for a small negative influence around 10°C. Surface salinity shows a clear influence impacting ppd positively with increasing salinity. Bottom salinity shows a similar pattern. The D-AT-SWT shows a negative effect at no or little difference between air and water. The teLatLong showed increasing detections from east to west, with no clear trend in latitude.

Environmental relationships for offshore stations (Group A)

Consistent with the GAM of data from Group AB stations, water depth, hardware version, detection threshold and month were non-significant factors in the model for Group A (Fig. 7). The influences of

Table 3. *Phocoena phocoena*. Detections of porpoises at different positions within a short time interval (<8 h) and hypothetical traveling speeds (v) >7 km h⁻¹. Date is given in the form dd.mm.yyyy. Δt : time difference between detections; Δs : spatial distance between detectors; -: not calculable

Pos. 1	Date and time of detection	Pos. 2	Date and time of detection	Δt (h, min)	Δs (km)	v (km h ⁻¹)	Minimum no. of groups
A12	13.12.2005 19:49	A4	13.12.2005 20:49	1 h	26.9	26.9	2
A14	04.01.2006 03:29	A12	04.01.2006 03:59	30 min	12	24.0	2
A8	10.01.2006 03:29	A6	10.01.2006 05:19	1 h 50 min	29.7	16.2	3
A8	10.01.2006 03:29	A2	10.01.2006 05:39	2 h 10 min	36.7	16.9	
A6	10.01.2006 05:19	A2	10.01.2006 05:39	20 min	12.5	37.5	
A5	17.01.2006 01:19	A2	17.01.2006 02:29	1 h 10 min	8.5	7.3	1–2
A15	17.04.2006 07:59	A11	17.04.2006 08:29	30 min	12.4	24.8	2
A2	02.03.2007 03:39	A14	02.03.2007 09:29	5 h 50 min	51.6	8.9	2
A10	07.06.2007 16:19	A8	07.06.2007 17:29	1 h 10 min	10.1	8.7	1–2
A1	28.06.2007 22:09	A2	28.06.2007 22:09	0 h	–	–	3
A1	28.06.2007 22:09	A7	29.06.2007 01:09	3 h	26.6	8.9	
A2	28.06.2007 22:19	A7	29.06.2007 01:09	3 h	30.3	10.7	
A4	29.06.2007 06:59	A11	29.06.2007 08:19	1 h 20 min	31.8	23.9	2

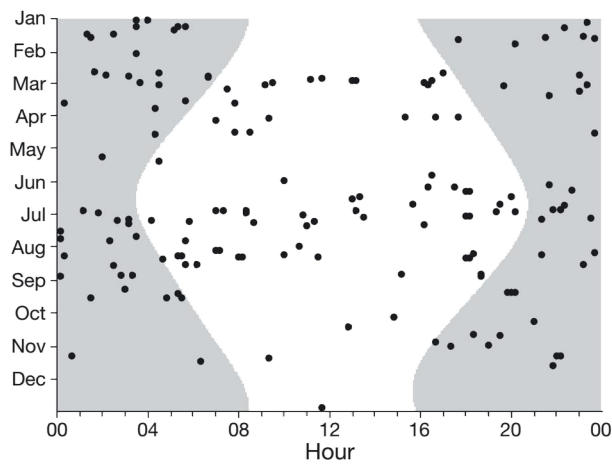


Fig. 5. Diurnal rhythm of detections (within 10 min bins, indicated by dots) in Pomeranian Bay (Group A). Grey areas are nighttime, and white areas are daytime

Ref-ppd, surface salinity and bottom salinity were not significant. The most important factors were the differences between years ($F = 39.963$, $p = 7.32 \times 10^{-10}$), followed by D-AT-SWT ($F = 11.855$, $p = 6.39 \times 10^{-4}$), teLatLong ($F = 4$, $p = 4.91 \times 10^{-4}$) and air temperature ($F = 3.742$, $p < 0.015$). The resulting model explains 27.9% of the deviance ($R^2 = 0.166$, $n = 387$, RMSEP = 3.1).

The variable year shows a clear positive relation (Fig. 7). D-AT-SWT still explains much of the deviance. There is a clear positive effect when air temperature is lower than surface water temperature, and negative effect when slightly above zero. In addition, low air temperatures of <2°C also have a positive effect on the ppd per month. In cases when air temperature is lower than surface water temperature while air

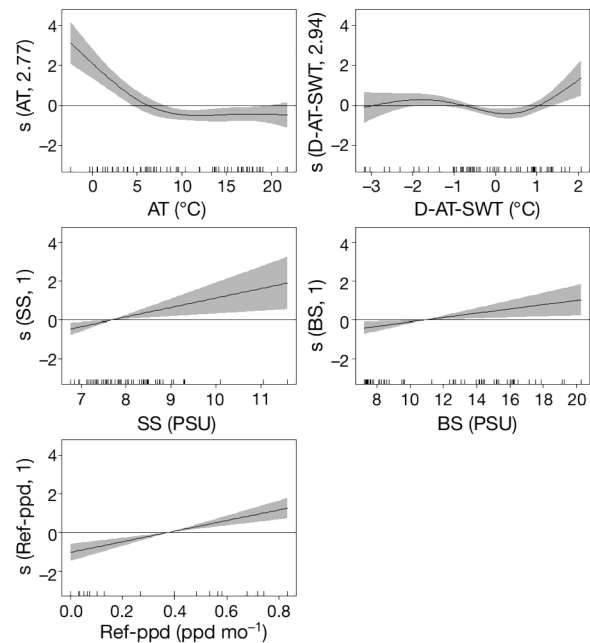


Fig. 6. Results of generalised additive models from stations in Group AB. Shown are the estimated smoothing splines (black line) for each significant variable in the backward selected model together with its 95% confidence limits (CLs, grey shaded areas) and estimated degrees of freedom (in brackets, y-axis). The horizontal black line at a y-value of zero indicates in which x-values a significant relationship with a factor was estimated. If the CLs are above or below the zero line the variable influences the model positively or negatively. Abbreviations as in Table 2

temperature is <2°C, the effects accumulate. The effect of teLatLong does not show a clear geographical trend, but explains much of the variance.

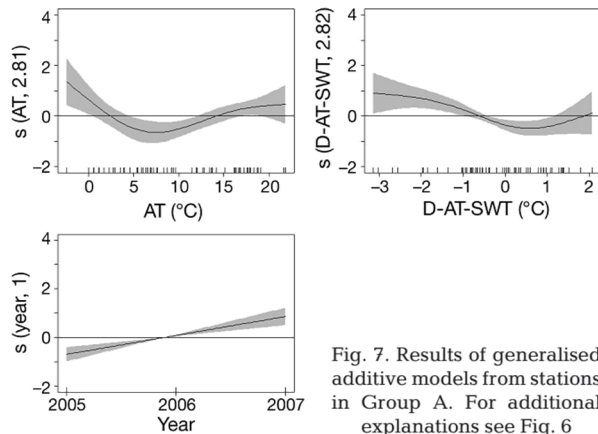


Fig. 7. Results of generalised additive models from stations in Group A. For additional explanations see Fig. 6

DISCUSSION

The BP harbour porpoise *Phocoena phocoena* population is 'Critically Endangered' (Hammond et al. 2008). Hence, a better understanding of seasonal migrations, geographic distribution and abundance of these animals is needed in adapting conservation measures. Previous research projects attempted to study habitat use and to estimate the abundance of this population with standard line transect surveys either from airplanes (Hammond et al. 2002, Berggren et al. 2004, L. Hiby & P. Lovell unpubl. data) or with visual observers and a towed hydrophone array from ships (Gillespie et al. 2005). None of these studies have succeeded in reliably estimating the abundance of porpoises in the Baltic due to extremely low sighting rates resulting in high confidence limits, but they proved that BP porpoises are highly endangered. We did not focus on estimating abundance, but succeeded in describing seasonal patterns and habitat use with 207 porpoise detections within a long-term study period.

The dataset presented here has low detection rates due to the low abundance of porpoises within the area. Detections were reviewed by visual inspection to ensure that only confirmed porpoise events were included in subsequent data analysis. Nevertheless, low detection rates lead to high model errors due to a high impact of zeros. Hence, all conclusions presented here have to be regarded as first results based on the best available methods.

The confirmation of several separate porpoise groups being registered within short times by pairing detections in a relatively small area is an important finding for the definition of critical areas to protect porpoises at certain times of the year. The detection

radius of T-PODs has been suggested to be considerably smaller than 500 m at the 127 dB re 1 μ Pa peak–peak (pp) detection threshold (Kyhn et al. 2008) and may not be extrapolated over a >350 m radius. Effective detection ranges are between ~32 and ~67 m for all click trains with detection thresholds of 125 dB re 1 μ Pa pp according to the form of analysis conducted by Kyhn et al. (2012). Hence, confirming that up to 3 groups of porpoises were present close to the monitoring stations could indicate that even more groups might have been present within the general area without being detected. As this part of the Baltic Sea is considered to be part of the distributional range of the BP population (Koschinski 2001, Huggenberger et al. 2002, Palme et al. 2004), all paired detections can be treated as BP registrations. To avoid by-catch during times with high porpoise occurrence, we suggest employing alternative fishing methods to gill nets, such as fish traps, as also proposed in the Jastarnia Plan (ASCOBANS 2009). Using acoustic harassment devices aims to exclude harbour porpoise from set-netting areas (Carlström et al. 2009). Exclusion from important habitats, however, may reduce the fitness and survival of the population. Due to spatio-temporal associations of porpoises and gill net fisheries (Herr et al. 2009), the use of an alternative gear instead of gill nets is desperately needed to reduce by-catch.

No obvious diurnal pattern was detected. Carlström (2005) showed diurnal patterns for high-density areas possibly linked to increased foraging activity during night. Patterns may vary depending on preferred prey species, habitat and season, as well as deployment and water depth; however, no such study has yet been conducted within the BP.

The GAMs for both data groups (of combined near- and offshore, and offshore stations alone, respectively) showed significant correlations with various factors. While the GAM of Group A (offshore stations) reacted mainly towards inter-annual differences and D-AT-SWT, as well as the parameter air temperature alone, the model of Group AB (all stations combined) showed a high impact of Stn 'Ref'. Its detections very probably represented mostly animals from the neighbouring IDW population that distribute during spring, summer and autumn throughout the areas west and north of Rügen (Verfuß et al. 2007, 2008a, Gilles et al. 2008, Scheidat et al. 2008). This is supported by findings from Denmark; animals tagged in Danish waters, most probably from the IDW population, usually stayed in Danish and western German waters—only a few strayed briefly into the BP near the southern coast of Sweden and in the

waters near Bornholm (Teilmann et al. 2011). We therefore conclude that data from near-shore stations on the east coast of Rügen have a high impact on the model of Group AB, adding the strong influence of migrating IDW animals that are registered in summer at these stations. Thus, the few detections of BP individuals with differing ecological preferences may hardly influence the model. This hypothesis is of course weakened by the fact that we cannot distinguish the 2 populations acoustically; theoretically, underlying ecological variables may hence cause both populations to migrate similarly. Nevertheless, genetic and morphologic differences have already been shown for the 2 populations, and physiological differences and adaptation to the less saline Baltic Basins are probable and would result in different ecological preferences.

As the influence of Stn 'Ref' was not significant in the model of Group A stations, there appeared to be fewer or no detections of IDW animals among these stations, and any summer peak in the offshore data may be due to a few IDW animals taking advantage of periods with increased prey availability as proposed by Scheidat et al. (2008). The influence of the factor 'year' might be biased by not covering the full year of 2007 and having fewer stations being recorded in the beginning of 2005.

The difference between air and water surface temperature is one of the strongest factors at Group A (offshore) stations, which suggests that BP porpoises remaining in the BP during winter, while IDW porpoises migrate westwards, are probably responding to the temperature gradient. We hypothesise that they move into ice-free waters to avoid confinement and possible suffocation due to ice cover in cold winters. This is supported by higher detection rates during low temperatures at both groups of stations. Once the temperature drops to a certain level, porpoises from the north-eastern parts of the BP might continue to migrate towards the saltier waters farther southwest. During summer, however, animals from the IDW might also use the area east of Rügen, when they appear to disperse throughout all parts of the German Baltic Sea. Therefore, BP porpoises appear to have a seasonal pattern of area use alternating with IDW animals. When including data influenced by IDW animals, population-dependent effects may thus be masked.

Surface and bottom salinity have an effect on the data of Group AB stations. This result underpins the findings of Edrén et al. (2010) who noted a large influence of bottom salinity on tagged animals in Danish waters. Salinity was not significant in Group

A, possibly pointing to different factors driving seasonal migrations for the 2 populations.

Cross validation showed that both models have a high model error and underestimated the importance of model factors when comparing the distribution of errors. Important information for a better understanding of habitat utilisation is therefore still missing, mainly due to low detection rates and ecological variables not incorporated into the model.

Nevertheless, the differences presented in habitat use add important information to the on-going conservation discussion. Distinct populations have genetical (Wiemann et al. 2010) and morphological differences (Huggenberger et al. 2002), but also differ in their ecological preferences, as presented here. Our dataset shows that porpoises in the German BP are scarcely encountered. It thus confirms that porpoises of the BP have become rare and are seriously endangered. Nevertheless, the existence of a BP population still appears to be evident in the different seasonal patterns as it is migrating south-westward into German waters, especially in cold winters. In the absence of detailed knowledge about the spring, summer and autumn distributions of this population, we support the employment of a large-scale use of SAM to an extended area of potentially preferred habitats in the BP, as is currently in progress through an EU-LIFE+ project called 'Static Acoustic Monitoring of Baltic Harbour Porpoises' (www.SAMBAH.org).

CONCLUSIONS

Static acoustic monitoring of a small part of the distributional range of porpoises *Phocoena phocoena* in the BP has enabled us to draw conclusions about the spatial and temporal distribution of harbour porpoises in this low-density area. This was not possible with previous visual abundance estimates. In winter, porpoises from the BP most probably move into the saltier German waters (less prone to freezing). Porpoises appear to predict ice-forming conditions via the empirical difference of surface water and air temperature or this co-variable serves as a proxy for another process that was not modelled. Although our data suggest that the distribution range of the IDW and BP populations possibly overlap geographically, the 2 populations appear to be separated by their temporal distribution pattern.

This implies a direct opportunity for conservation measures, because now — for the first time — data on the temporal and spatial distributions of BP porpoise are available for German waters. Acoustic detection

rates are low, indicating that the BP population is currently extremely small and at risk of extinction. Conservation actions must be taken immediately to have an effect. Therefore, European legislation such as by-catch regulation EC 812/2004 (EU Council 2004) needs to be improved immediately to ban the use of gill nets in critical parts of the BP, at least at certain times of the year. Other measures such as the use of pingers may not prevent anthropogenic mortality sufficiently and leave Baltic harbour porpoises at further risk.

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4 Methodology and results of calibration of tonal click detectors for small odontocetes (C-PODs)

Static acoustic monitoring (SAM) is one major technology for observing small cetacean species. Automatic click loggers deployed for long time periods (> 2 months) with a single hydrophone are one standard solution. Acoustic properties, like detection thresholds of these instruments, are essential for interpretation of results, but have nevertheless received little attention. A methodology for calibrating tonal click detectors in small tanks consisting of the determination of the horizontal directivity pattern and detection thresholds including a transfer function is presented. Two approaches were tested to determine detection thresholds by a) determining the 50 % detection threshold and b) fitting a linear regression model to the recorded relative amplitudes. The tests were carried out on C-PODs (Cetacean PODs, tonal click detectors), the most commonly used instrument for SAM in Europe. Directivity and threshold were tested between 60 and 150 kHz. Directivity showed a maximum variation of 8.5 dB in the horizontal plane. Sensitivity is highest between 80 and 130 kHz and linear (± 3 dB) in this frequency range for most of the instruments tested. C-PODs have a detection threshold (calculated with the linear model) of 114.5 ± 1.2 (standard deviation) dB re 1 μ Pa peak-peak at 130 kHz.

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The major components of a C-POD (© Michael Dähne/ITAW)

Methodology and results of calibration of tonal click detectors for small odontocetes (C-PODs)^{a)}

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Static acoustic monitoring (SAM) is one major technology for observing small cetacean species. Automatic click loggers deployed for long time periods (>2 months) with a single hydrophone are a standard solution. Acoustic properties, like detection thresholds of these instruments, are essential for interpretation of results, but have nevertheless received little attention. A methodology for calibrating tonal click detectors in small tanks consisting of the determination of the horizontal directivity pattern and detection thresholds including a transfer function is presented. Two approaches were tested to determine detection thresholds by (a) determining the 50% detection threshold and (b) fitting a linear regression model to the recorded relative amplitudes. The tests were carried out on C-PODs (Cetacean PODs, tonal click detectors), the most commonly used instrument for SAM in Europe. Directivity and threshold were tested between 60 and 150 kHz. Directivity showed a maximum variation of 8.5 dB in the horizontal plane. Sensitivity is highest between 80 and 130 kHz and linear (± 3 dB) in this frequency range for most of the instruments tested. C-PODs have a detection threshold (calculated with the linear model) of 114.5 ± 1.2 (standard deviation) dB re 1 μ Pa peak-peak at 130 kHz. © 2013 Acoustical Society of America. [<http://dx.doi.org/10.1121/1.4816578>]

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I. INTRODUCTION

Static acoustic monitoring (SAM) of small and large cetaceans is one major technology for observing populations difficult to assess with other more traditional monitoring techniques like aerial and shipboard surveys or photo-identification (Marques *et al.*, 2009; Gallus *et al.*, 2012; Kyhn *et al.*, 2012; Sasaki-Yamamoto *et al.*, 2012). One approach is to use hydrophone arrays for estimating the distance to the animal detected (reviewed in Mellinger *et al.*, 2007). Another method is the use of automatic long-running stand-alone single hydrophone detectors, which is the most common approach. With the latter distance estimation to the animal based on the recorded data is nearly impossible. If detection rates or other cues shall be interpreted as animal occurrence rates or even abundance, the sensitivity of the instruments is crucial when comparing the results of different loggers (Verfuß *et al.*, 2010). Differing sensitivities will

result in a change in observed acoustic space that needs to be accounted for.

One widely used instrument is the T-POD (Timing porpoise detector, Chelonia Ltd., U.K.), a single hydrophone energy detector. Studies using T-PODs were conducted to investigate possible differences in the reaction of harbor porpoises (*Phocoena phocoena*, L. 1758) with regards to various fishing gear (Carlström *et al.*, 2009; Koschinski *et al.*, 2006), as well as in monitoring studies (Verfuß *et al.*, 2007; Verfuß *et al.*, 2008b) and environmental impact assessments (Carstensen *et al.*, 2006; Tougaard *et al.*, 2009; Brandt *et al.*, 2011). C-PODs (Cetacean PODs, Chelonia Ltd., U.K.), the digital successor of the T-POD were developed in 2008 as a tool to monitor different odontocete species by recording their echolocation clicks simultaneously. This addressed one major short-coming of the T-POD which was only able to differentiate more than one species by assigning different settings to alternating time periods as described in Philpott *et al.* (2007). Most recently C-PODs were used to successfully monitor harbor porpoises entering the river Weser, Germany (Wenger and Koschinski, 2012) to test the effectiveness of pingers (Hardy *et al.*, 2012) and to investigate whether environmental DNA would be an appropriate method to monitor marine mammals (Foote *et al.*, 2012). As the T-POD is out of production nowadays, C-PODs or other devices will be used more and more for impact assessments (Dähne *et al.*, 2013), monitoring schemes and assessment of the status of endangered populations of small odontocetes.

^{a)}Parts of this work were presented as a poster at the annual meeting of the European Cetacean Society in Istanbul 2009.

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Other devices used as stationary click-detectors are the stereophonic A-Tag (Akamatsu *et al.*, 2008) and the single hydrophone Porpoise Click Logger (PCL or Aquaclick 100, Aquatec Group Ltd., U.K.).

While all of the studies mentioned above measured relative porpoise abundance by using acoustic detections as a proxy for harbor porpoise presence, little is known about how this relation can be defined and how it can be used to make results comparable across studies. Tougaard *et al.* (2006) suggested that this relationship can be defined if a detection function or at least an effective detection range can be estimated, which might be greatly affected by the sensitivity of the instruments used. Kyhn *et al.* (2008) continued this thought by linking T-POD performance in test tank trials to field experiments. They showed that a relationship exists and that differences in detection rates can be quite dramatic, resulting in a large variation of the parameters analyzed. This will present some difficulties for instance for an abundance estimate within a point transect sampling design as proposed by Kyhn *et al.* (2012). For C-PODs, however, no such studies have been yet performed, and hopefully standardization of their sensitivity will be much tighter compared to what is found in T-PODs. Studies on different T-POD generations already showed a tighter standardization with increasing version number (Dähne *et al.*, 2006; Verfuß *et al.*, 2008a; Verfuß *et al.*, 2008b; Verfuß *et al.*, 2010; Verfuß *et al.*, 2013). While calibration of hydrophones, amplifiers, and recording equipment for underwater and airborne sound are very well standardized (e.g., IEC 60565 (2007); IEC 61094-1/2/3/4/5; ANSI, 2012), calibration of single hydrophone click detectors for recording underwater wildlife is currently only done occasionally and not in a systematic fashion. One major problem is that it is not possible to calibrate click detectors like hydrophones (Levin, 1973; IEC 60565 (2007); ANSI, 2012) by measuring the voltage response of the receiving hydrophone, because the analog and digital electronics and detection mechanisms may essentially alter the frequency response of the hydrophone. For instance calibration data is provided for the PCL and the A-Tag only for the hydrophone by measuring the voltage response, but not for the unit itself.

Results of calibration of T-PODs showed considerable variation in sensitivity and omnidirectionality (Kyhn *et al.*, 2008; Verfuß *et al.*, 2010; Verfuß *et al.*, 2013). This variation comes from the production process of the devices including (a) the piezo-ceramic element being embedded into a robust plastic housing and (b) variation of the piezo-ceramic element itself. To keep costs at a minimum it is often more effective to buy cheaper elements with larger production variations and test and evaluate them later, than buying high quality hydrophone elements. Hence the instrument sensitivity is partly underlying stochastic variations.

Akamatsu *et al.* (2002) demonstrated that tests in small laboratory tanks are difficult, but can still lead to valid results, when the setup is thoroughly planned taking the size and acoustic properties of the tank into account. In this study, we developed a methodology to calibrate tonal click detectors like the C-POD with reasonable effort and performed laboratory trials in a test tank with 86 C-PODs to

estimate the variation in sensitivity. Furthermore, reasoning why calibration of these instruments is necessary and should be repeatedly conducted is provided.

II. METHODS

Measurements were carried out in a $0.7\text{ m} \times 1.0\text{ m} \times 0.68\text{ m}$ fiber glass test tank (Fig. 1) using calibrated hydrophones as receiver (TC 4013, TC 4014, RESON A/S, DK) and transmitter (TC 4013, RESON A/S, DK). The setup in the calibration tank shown in Fig. 1 is partly derived from Levin (1973). The transmitter was used to send out packets of 10 signals [15 cycles sine wave signals in cosine envelope, Figs. 2(c) and 2(d) in comparison to a porpoise click in Figs. 2(a) and 2(b)] at ten frequencies (60 to 150 kHz in 10 kHz steps) with a data acquisition card (PCI-6110E, National Instruments, USA) using circuit diagrams designed in DasyLab 7.0 (Measurement Computing, Germany). The amplitude of each outgoing frequency signal was adjusted by the transmitting hydrophone's calibration curve in such a way that equal pressure levels at the receiver were ideally established, resulting in peak–peak pressure levels of 146 dB re $1\text{ }\mu\text{Pa}$ at 1 m equaling 20 Pa peak–peak at 1 m. Signals were sent with a sampling rate of 1 MS/s and attenuated when required via DasyLab.

The signal was then picked up by the receiving hydrophone, amplified and bandpass filtered (100 Hz to 360 kHz) with a B1501 amplifier (ETEC, DK). Gain of the amplifier was measured and later used for calculating the receiving level. The amplified signal was digitized with the same National Instruments soundcard via DasyLab at 1 MS/s and peak–peak measurements were taken using Avisoft 2.2 and 4.52 (Saslab, Germany). The resulting received levels were used as baseline measurements. The receiving hydrophone was then replaced by a C-POD for sound exposure to the calibration signals.

Sender and receiver (Hydrophones and C-PODs) were installed in mid water depth, centered in the pool with a distance of 0.5 m to each other so that the direct signal was perceived completely by the receiver before the arrival of any echo. Signal length did not allow for a calibration below 60 kHz due to a prolonged duration of the signal compared to higher frequencies leading to an overlap between signals

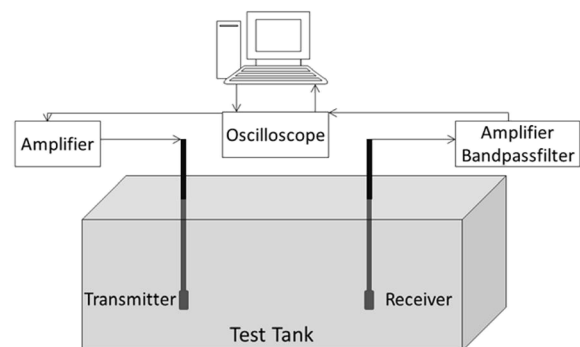


FIG. 1. Setup of test tank. The receiving hydrophone was replaced with a C-POD at exactly the same position where the received level was measured.

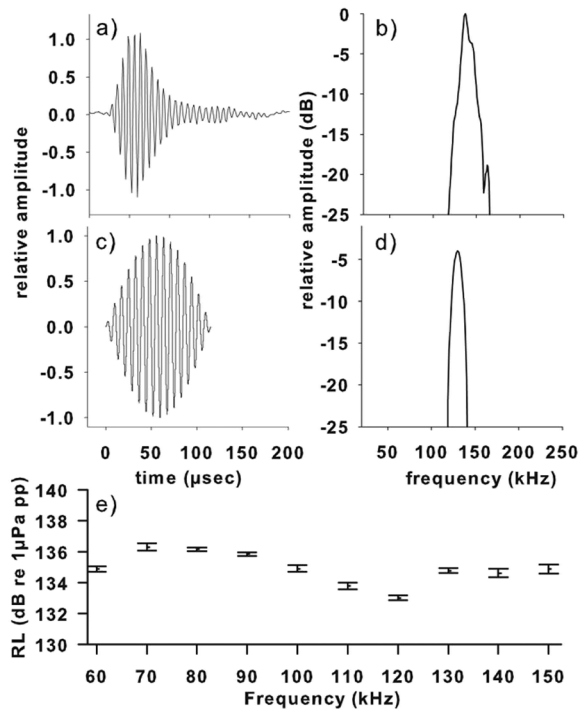


FIG. 2. Example of a harbor porpoise click (a) waveform, (b) power spectrum; the used calibration signal at 130 kHz (c) waveform, (d) power spectrum and (e) the mean received peak-peak levels and their standard deviation (error bars) during 14 calibration trials. For each calibration 10 clicks were evaluated to estimate the mean received level.

on the direct path and echoes (described in more detail in Levin, 1973). The upper frequency limit (150 kHz) was chosen in accordance with the reported properties of the C-POD having a high frequency cut off at approximately 160 kHz. A positioning system was used to ensure that the accuracy of the positioning of the acoustic centers of hydrophones were within ± 0.5 cm (hydrophones) and for the C-PODs within ± 2 cm. Angles were marked and lined up during the calibration. Calibration instruments and C-PODs were marked, so that each device could be removed from the circuit and be reinstalled in exactly the same position. All tests were monitored using a digital oscilloscope (Tektronix: TDS-210).

To assess the accuracy of repeated measurements one C-POD was calibrated five times, performing all tasks. The deviation between the measurements was determined and used as an indicator how accurate measurements can be duplicated.

A. C-PODs

C-PODs are autonomous data loggers which monitor the frequency band between 20 and 160 kHz. This band includes the echolocation frequencies of most odontocete species except for sperm whales. By analyzing the time-amplitude signal they estimate parameters of acquired waveforms (zero-crossings, frequency content, peak amplitude, bandwidth, parameters of the envelope) and determine whether the recorded sound has tonal components. If the criteria for

tonality are met then all parameters are saved to a nonvolatile memory. C-PODs can handle up to 16 GB SD (Secure Data)-cards and run on 10 D-Cells for approximately 5 months' time. While T-PODs had a variety of settings to adjust the monitored frequency of interest to specific odontocete species, C-POD have only minimal user-defined settings in order to keep comparability of datasets. There is also no need for species tuning, as the whole frequency range can be monitored simultaneously. C-PODs can be easily handled and used by non-acousticians, but have a few drawbacks because of this simplicity, for instance the usage of non-standard units and not recording full waveforms for later analysis to save battery and memory space. Broad-band hydrophone systems on the other hand require large storage capacities or fast data uplinks if used for long-term monitoring. C-PODs pick up sound by a custom made piezoelectric hydrophone and convert the voltage into 8-Bit values (digitization levels) representing relative peak-peak pressure amplitudes (termed Ppp in the C-POD's proprietary software). For clarity, these digitization levels are uncorrected for hydrophone sensitivity at different frequencies and possibly other instrument internal signal processing and will be referred to within this paper as dPpp. We have used peak-peak pressure levels throughout this paper as it fits to the output of the C-POD itself. While older version zero C-PODs were usually set to a minimum registered dPpp value of 5 digits to reject electronic noise and very weak clicks, newer ones are set to 12 digits, giving it a range of 12 to 255 integer values to represent amplitudes as dPpp. To give consideration to this, in the present study, the C-PODs were either set to a minimum dPpp value of 12, or values below 12 were eliminated using a database query in later analysis. Otherwise standard settings as provided by the manufacturer were used. V1 C-PODs (not used within the present study) have a minimum setting of 3 dPpp.

B. Receiving beam pattern

Eighty-six C-PODs were calibrated on 16 positions along their horizontal axis in 22.5° steps to determine the directionality of the receiving beam pattern. First position was repeated to control for variation. C-PODs were marked to enable the use of the same 16 positions in further calibrations, allowing for a direct comparison. At each position 50 signals per frequency were transmitted. Series of 50 signals per packet for the frequencies 60 to 150 kHz were sent out for each angle resulting in 800 signals per C-POD altogether. Signals were sent out in 25 ms intervals to allow all echoes to fade before the next click was transmitted. The standard maximum receiving level, any C-POD was exposed to, was set to 140 dB re $1 \mu\text{Pa}$ peak-peak. Because of an unexpected variability in sensitivity between measuring devices, the transmitted level had to be reduced by up to 5 dB for some very sensitive devices. This difference was accounted for by back calculating the results of all measurements to a standard value of 135 dB re $1 \mu\text{Pa}$ using a linear regression based on the data and method described in the next chapter. Figure 2(e) shows the accuracy of the receiving level as recorded by the calibrated hydrophone corrected for its transfer function before the standardization to a received

peak–peak Level of 135 dB re μPa at each frequency step. Raw click data (dIPpp, time and frequency of each click) were stored in an MS Access database. A custom programmed Visual Basic (VB) routine cleaned the raw click data from echoes. Median dIPpp values were calculated for each frequency and plotted. Analysis was performed using R 2.11.0 (R Development Core Team, 2011).

C. Detection thresholds and relationship between receiving level and dIPpp-values

To determine the detection thresholds and the relationship between receiving level and the corresponding dIPpp-values, we employed two analysis methodologies; 50% detection thresholds and linear regression models, both based on the same calibration procedure: Series of 100 signals per packet for the frequencies 60 to 150 kHz were sent out with decreasing amplitude. First two steps were attenuated by 3 dB each and then each step further was 2 dB less, with 18 steps in total, covering a range of 36 dB. Click interval was the same as for the receiving beam pattern. The procedure was carried out at four positions in the horizontal plane. The received raw C-POD click-data were stored in an MS Access database with custom programmed VB routines that deletes data arisen from echoes of the direct calibration signals formed in the tank and analyzes the large dataset as described below. The VB routine includes the calculation of received levels by taking the received voltages and amplification as well as hydrophone sensitivities into account. The resulting received levels were plotted; the two detection thresholds as described below were calculated and the difference between 50% detection threshold and linear regression slope and intercept was determined.

1. Determining the 50% detection thresholds

To determine 50% thresholds (RL_{50}), all recorded clicks within each packet were counted and the two series with the closest values to 50 recorded out of 100 transmitted clicks were determined. A linear relation between those two points was assumed and the dIPpp value for 50 received clicks and the corresponding receiving level was calculated with a linear interpolation. Analysis was automated using Visual-Basic procedures under Microsoft Access.

2. Linear model

Generalized linear mixed models were calculated under R 2.11.0 (R Development Core Team, 2011) and the library lme4 (Bates and Maechler, 2010) using $20 \log(dIPpp)$ as the dependent and the corresponding received peak–peak pressure level (RL) as the explanatory variable. Two models for each C-POD at each frequency were derived—one with position as a random factor (1) and one without (2).

$$20 \log(dIPpp_{ij}) = \alpha_j + \beta_j RL_{ij}, \quad (1)$$

$$20 \log(dIPpp_i) = \alpha + \beta RL_i, \quad (2)$$

where α is the intercept and β the slope of regression, while i denotes the different amplitude steps at different positions (j) following Zuur *et al.* (2007).

The two models were compared using an analysis of variance (ANOVA), and all data sets, for which the two were different from each other, handled very restrictive at $p\chi^2 < 1$ (error level of the ANOVA), were excluded from further analysis. The reason for this procedure was that four positions might not lead to a good estimate of the detection threshold if the instruments have a very uneven horizontal directivity pattern leading to either different slopes or different intercepts of the linear regression; hence only PODs with sufficiently low variation within the horizontal plane were used for the threshold determination: The slope and intercept of the regression line were determined, derived from the values gained at all four positions following model (2). Slope and intercept were applied to the data retrieved in receiving beam pattern test to calculate the dIPpp value for a standard receiving level of 135 dB re $1 \mu\text{Pa}$ peak–peak. Furthermore, the corresponding receiving level was calculated for a dIPpp value of 12 with the linear model (RL_{LM}) as second mean of threshold determination, and compared to the RL_{50} .

III. RESULTS

A. Receiving beam pattern

The calibrated 86 C-PODs are generally more sensitive in the frequency band between 80 and 130 kHz and are less sensitive below 80 kHz and above 140 kHz (Fig. 3, Fig. 4). The confidence limits at 130 kHz are generally low. The dIPpp values of the instruments range between 175 and 60, which correspond to a maximum difference of 9.3 dB in receiving level (Fig. 4). Horizontal variation within a single C-POD can reach up to 130 digits (e.g., C-POD 98 at 110 kHz, Fig. 5) on the 8-Bit dIPpp scale, corresponding to a difference of 8.5 dB in receiving level, using a slope of one and an intercept of -92 as determined by the mean model of the threshold test (see Sec. III B). Nevertheless, most instruments are omnidirectional within ± 3 dB range. For example Fig. 5 shows the frequency dependence of the dIPpp values for a receiving level of 135 dB re $1 \mu\text{Pa}$ for two individual C-PODs from the same series (numbers 96 and 98). While the median for 130 kHz is similar, the variation in the receiving beam pattern leads to different sized boxes and whiskers. C-POD 98 has a much higher horizontal variation than C-POD 96.

The single C-POD calibrated five times to assess measurement accuracy showed that the dIPpp during the receiving beam pattern test varied with a standard deviation of 0.9 digits (maximum range of 5.6 digits difference).

B. The 50% detection thresholds and linear model

The receiving beam patterns of $n = 86$ C-PODs between 100 and 140 kHz; $n = 44$ for 60 and 80 kHz; $n = 46$ for 150 kHz qualified for the calculation of a regression line to determine the detection threshold via the linear model approach. Two C-PODs (96 and 98) were chosen as examples for how the threshold determination is carried out and to show differences in individual instruments. C-POD 96 has a nearly homogenous receiving beam pattern, while C-POD 98 has a wider variation in the horizontal plane (Fig. 6). The

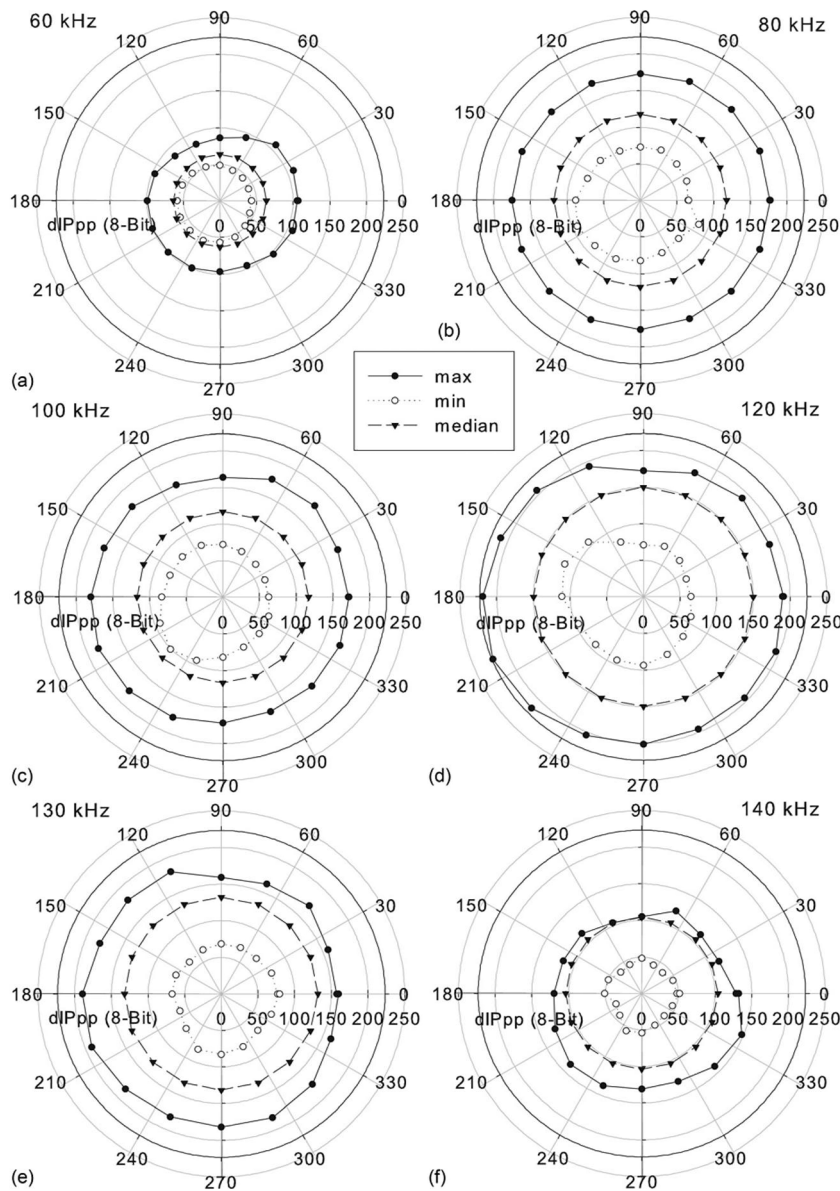


FIG. 3. Horizontal directivity at (a) 60, (b) 80, (c) 100, (d) 120, (e) 130, (f) 140 kHz scaled to 135 dB re 1 μ Pa pp receiving Level. Shown are the dIPpp-values as an unadjusted measure for relative sound pressure. Shown are the C-PODs with the maximum sensitivity (solid line with full circles), minimum sensitivity (dotted line with hollow circles) and median dIPpp of all C-PODs tested (dashed line with triangles).

receiving level at the 50% threshold of C-POD 96 is similar to the threshold determined with the linear regression model for an intercept at $dIPpp_{12}$. These values differ in C-POD 98, with the RL_{50} being about 4 dB higher than RL_{LM} . The drop off in recorded clicks with decreasing amplitude is less steep for C-POD 98 than for 96. However, the difference in RL_{LM} for both instruments is less than 1 dB, while the difference in RL_{50} is 4 dB.

For all frequencies variation of C-PODs for RL_{50} and RL_{LM} is quite small, with 50% of the data in a 2 to 3 dB range (Fig. 7). Minimum–maximum ranges are mostly less than 10 dB, but for 140 and 150 kHz C-PODs have a wider variation.

Results of the linear models and the 50% thresholds are very similar for all frequencies except 140 and 150 kHz,

where receiving levels are higher for the RL_{50} . An overview of the differences between the RL_{50} and RL_{LM} for 130 kHz calibration signals is given in Fig. 8. In most measurements, RL_{50} was lower than RL_{LM} . This was the case for all frequencies above 120 kHz. Below 120 kHz a symmetric distribution can be seen. To get a better understanding of the relationship between received level and registered $20 \log(dIPpp)$ values, we investigated the slope and intercept of the linear regression models (Fig. 9). While the slope is very close to 1 for all frequencies, showing a linear amplitude response, the intercept varies showing the differences in sensitivity at tested frequencies. An appropriate mean amplitude model for 130 kHz would hence be

$$RL_{pp} = 20 \log_{10}(dIPpp) + 92.$$

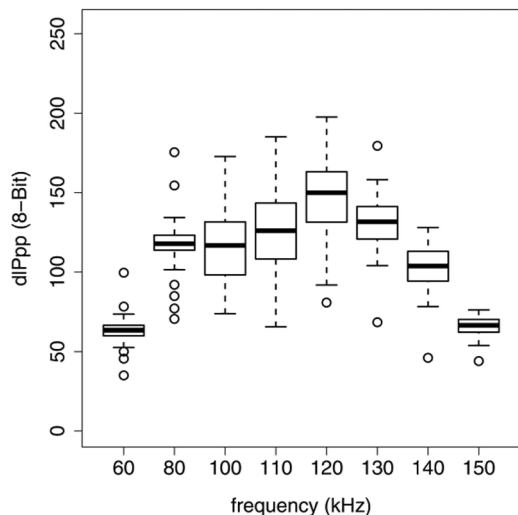


FIG. 4. Box plot of all directivity results scaled to 135 dB re 1 μ Pa pp receiving level. Shown is the 5%, 25%, 50%, 75%, and 95% percentile and outliers of the median dIPpp values per position as recorded by the C-PODs for test signals of different frequency with a receiving level scaled to 135 dB re 1 μ Pa. Devices are calibrated by the manufacturer at 130 kHz. Hence a small variation for this frequency should be given, other frequencies are not calibrated and hence have higher variation. Number of calibrated PODs are at 60 and 80 kHz: $n = 44$; 100–140 kHz, $n = 86$; 150 kHz: $n = 46$.

RL₅₀ derived from calibrating a C-POD five times varied with a maximum standard deviation of 0.4 dB and the absolute maximum difference between thresholds found was 0.9 dB. For the linear model threshold RL_{LM} the differences were smaller (<0.1 dB standard deviation and 0.2 dB absolute maximum difference between thresholds found) showing that the method is more robust with regard to sampling error.

C-PODs have a detection threshold (linear model) of 114.5 ± 1.2 (standard deviation) dB re 1 μ Pa peak–peak at 130 kHz. The difference between the most and least sensitive instrument was found to be 7.1 dB re 1 μ Pa peak–peak.

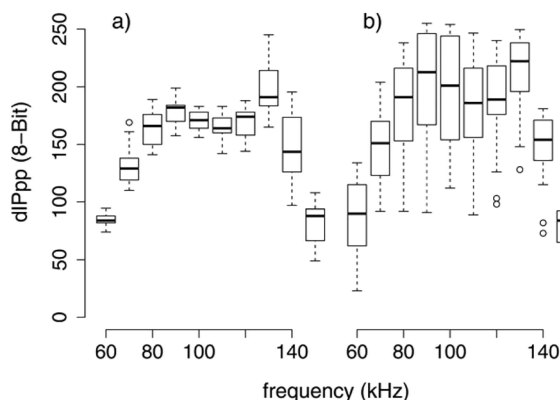


FIG. 5. Box plot showing the 5%, 25%, 50%, 75%, and 95% percentile and outliers of the recorded unadjusted dIPpp values obtained for two exemplarily chosen individual C-PODs (a) 96 and (b) 98 at 16 horizontal positions for test signals of different frequencies with a receiving level of 135 dB re 1 μ Pa.

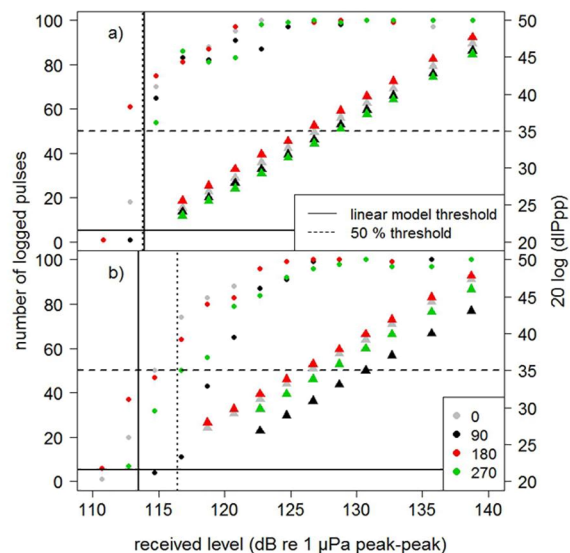


FIG. 6. (Color online) Deriving detection thresholds for two exemplarily chosen C-PODs (a) 96 and (b) 98 at 130 kHz. Number of clicks logged (left y axis, solid circles) and measured dIPpp values log-transformed with 20 log (dIPpp) as returned by the C-POD (right y axis, triangles, values containing less than 80 recorded clicks are omitted). The dashed vertical line indicates the receiving level at the 50% threshold (RL₅₀), the point, where only 50% of the emitted clicks (horizontal dashed line) are detected, while the solid vertical line indicates the receiving level for the dIPpp-value at 12 (horizontal solid line) calculated with a linear regression of the dIPpp values (RL_{LM}). C-POD 96 does not have a large variation in directivity and both thresholds are alike. C-POD 98 has a large variation in directivity and the RL_{LM} is 4 dB smaller than the RL₅₀.

IV. DISCUSSION

The hereby presented procedure can be used by any acoustically educated SAM-user with limited equipment: A calibration tank, two calibrated hydrophones, and calibrated data acquisition hardware including amplifiers to test devices individually within a short period of time. Devices like the T-POD, PCL, and the A-Tag filter sound at very specific target frequency and were mostly deployed for porpoise species using narrow band high frequency clicks at ~ 130 kHz. However, T-PODs were also used for monitoring of dolphin species using clicks covering a larger band (Philpott *et al.*, 2007). For those detectors calibration procedures specifically designed for the target species like presented by Dähne *et al.* (2006), Kyhn *et al.* (2008), Kyhn *et al.* (2012), and Verfuß *et al.* (2010, 2013) are feasible. For tonal detectors covering a wide frequency range as done by the C-POD, this has to be accounted for, and the hereby presented method is adequate to analyze the properties of individual instruments.

The calibration of automatic click detectors as presented in this study enables an assignment of digitization levels to absolute peak–peak pressure levels. The dIPpp-values for amplitudes returned by the C-POD represent quite accurate measurements on a relative scale for each tested frequency. However, these values are not comparable between frequencies without prior correction for the frequency response of each individual logger.

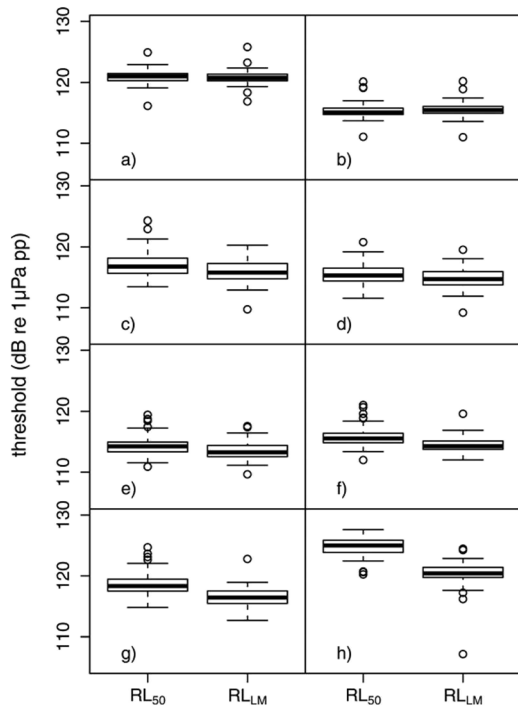


FIG. 7. Box plots showing the 5%, 25%, 50%, 75%, and 95% percentile and outliers of RL_{50} and RL_{LM} for calibration signals of (a) 60 kHz, $n=44$, (b) 80 kHz, $n=44$, (c) 100 kHz, $n=86$, (d) 110 kHz, $n=86$, (e) 120 kHz, $n=86$, (f) 130 kHz, $n=86$, (g) 140 kHz, $n=86$ and (h) 150 kHz, $n=46$. While results are comparable for frequencies up to 120 kHz, the 50% detection threshold seems to underestimate sensitivity from 130 kHz upward.

The calibration procedure shows that omnidirectionality is achieved by C-PODs within 3 dB, with the occasional outlier. Linearity in terms of frequency response (± 3 dB accuracy) is given for the frequency range between 80 and 130 kHz. The newer version 1 C-PODs should extend this range to approximately 150 kHz. Wild harbor porpoises were reported to have centroid frequencies of 130–142 kHz and peak frequencies of 129–145 kHz (Villadsgaard *et al.*,

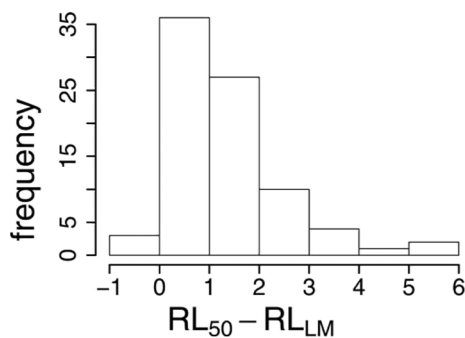


FIG. 8. Histogram of the differences between RL_{50} and RL_{LM} derived for 130 kHz calibration signals ($n=86$). The histogram shows a left skewed distribution, indicating, that the error is systematic. Most probably a 50% detection threshold underestimates sensitivity by relying on weak clicks with a bad signal to electronic noise ratio interfering with electronic devices at the calibration site, while the RL_{LM} is based on amplitudes with much better signal to noise ratios.

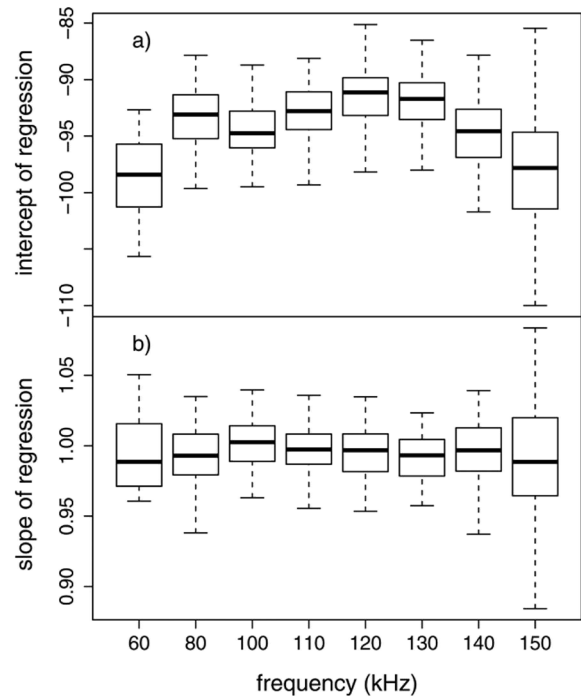


FIG. 9. Intercept and slopes of the linear regression models: Intercepts represent the sensitivity of the devices with respect to frequency, while a slope of 1 ± 0.025 is given for 50% of the C-PODs at each frequency except for 150 kHz. For electronic equipment this value should be calibrated to be 1, but differences of 0.025 would lead to a maximum difference of ± 1.2 dB for the full amplitude range at 8-Bit resolution.

2007). Hence, the sensitivity difference between 130 and 140 kHz as reported here (version 0 C-PODs), can influence the data comparability when using different versions of C-PODs within a study (version 0 and 1). Especially for multi species studies, like simultaneous recordings of bottlenose dolphins and harbor porpoises, the reduced sensitivity for the lower and broader dolphin frequency band (e.g., Au and Hastings, 2008) should be considered.

These findings are in line with the standardization by the manufacturer. Instruments are calibrated using a setup that standardizes the amplitude scale but not the detection threshold so that a common uniform detection threshold can be set retrospectively, with a digit value of 12 being the standard for version 0 C-PODs. This procedure is carried out in a small calibration tank with very little reverberation. A signal of fixed amplitude (130 kHz sine wave signal in a rectangle envelope) is transmitted and then received by the C-POD. The C-POD is continuously rotated during this procedure and the gain value is adjusted so that the mean dIP_{pp} of a large number of radial positions for the received level is 50. C-PODs are calibrated to work uniformly at 130 kHz within reasonable limits—the variation itself is much smaller than reported for T-PODs of different versions by Dähne *et al.* (2006); Kyhn *et al.* (2008), Kyhn *et al.* (2012), Verfuß *et al.* (2008a), Verfuß *et al.* (2010) and Verfuß *et al.* (2013).

Determining the detection threshold with a linear regression model turned out to be a more reliable method than the 50% threshold method, especially at higher frequencies; the

projected signals were at some occasions not properly picked up by some C-PODs, most likely caused by electromagnetic interference of instruments, like pumps and engines used in the daily business of the calibration location within a large aquarium. This has a larger effect on instruments with higher horizontal variation. As this is a calibration setup problem, this would not show up in C-PODs operating at sea, hence using a 50% detection threshold might then be misleading. For stationary click loggers recording a pressure equivalent, like the C-POD, it is possible to use the linear model method instead of the 50% detection threshold and this should then be preferred.

As variation even at 130 kHz occurs and is not negligible, a regular test tank calibration is recommended to ensure, that devices are still working within their specifications. Hard knocks due to at sea handling in rough conditions may affect the acoustic properties of the devices more heavily than a possible slight change in sensitivity over time. At present, only a few instruments have been repeatedly calibrated with the presented calibration procedure in a comparably short time frame. Therefore significant changes in sensitivity that were seen in T-PODs due to knocks and repairs (Verfuß *et al.*, 2010, 2013) were not yet shown for C-PODs. If a regular calibration is not possible, it is advisable to perform comparison deployments using all instruments simultaneously to monitor the same area in various locations, to find at least the outliers with very high or very low sensitivities. Nevertheless, this cannot replace proper test tank trials. Instruments should ideally be calibrated prior deployment and from there on, once every year to capture sensitivity changes over the course of time or due to instrument failure/defects. If a significant change in sensitivity shows up in repeated calibrations, then it is not possible anymore to attribute sensitivity to corresponding datasets. Thus data might have to be discarded. Even when conducting regular calibrations, instruments should be rotated in between monitoring positions to rotate the instrument's error as well. Procedures can be simplified for a repeated calibration after initial assessment. For instance it would be possible to perform a fast directivity test at 130 kHz instead of testing the whole frequency spectrum. If directivity and received dLppp did not change, then all other properties most probably have not changed as well.

The variation in C-POD sensitivity documented here is not very large and comparable to high quality hydrophones usually calibrated to ± 2 or ± 3 dB. However, one has to be aware, that a change in sensitivity of T-PODs of 9 dB was directly linked to an increase of recorded raw clicks from ~ 1.600 clicks at the least sensitive to ~ 3.000 clicks at the most sensitive T-POD (a POD of similar sensitivity even recorded 3.600 clicks) in a study by Kyhn *et al.* (2008). As the circumstances are not very much different for C-PODs even small changes in sensitivity may lead to significantly different results in field data.

V. CONCLUSION

Our results indicate that an extensive testing of single hydrophone detectors is necessary before use of new

equipment in field studies to provide detailed knowledge on their acoustic properties. A large variability in detection thresholds could lead to drastically different results, when no correction is applied to the data. A correction could be applied by including the detection threshold in modeling approaches. For C-PODs the differences in detection thresholds at 130 kHz are small, indicating that their detection abilities in field trials should be comparable. However studies using calibrated C-PODs in field comparisons have not yet been published.

The sharp drop off in sensitivity below 80 kHz holds implications for multi species surveys as it affects the comparability of data when monitoring species' vocalizations over a wide range of frequencies.

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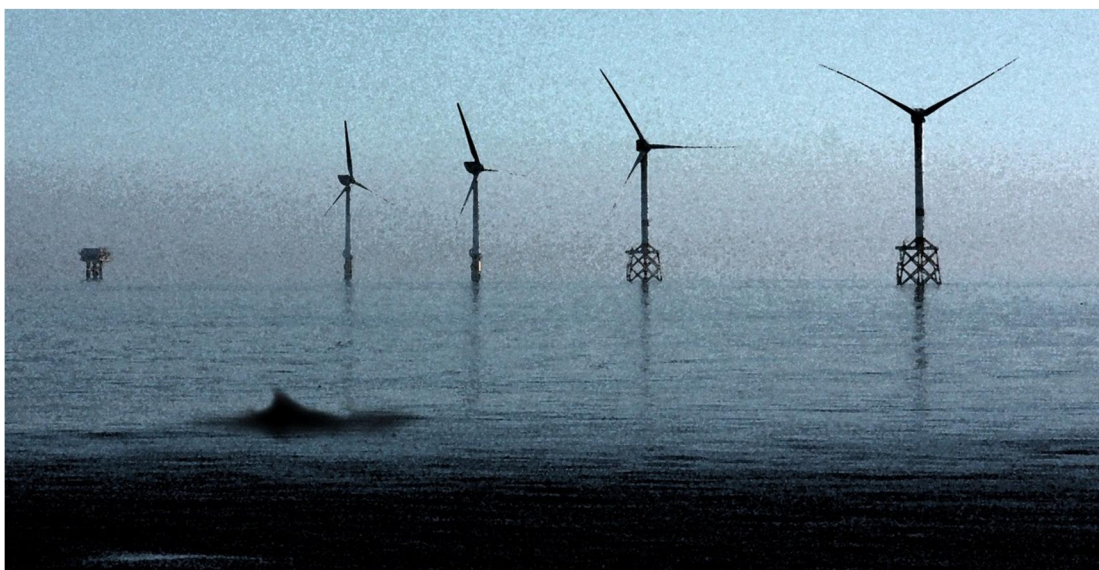
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5 Effects of pile-driving on harbour porpoises (*Phocoena phocoena*) at the first offshore wind farm in Germany

The first offshore wind farm ‘*alpha ventus*’ in the German North Sea was constructed north east of Borkum Reef Ground approximately 45 km north off the German coast in 2008 and 2009 using percussive piling for the foundations of 12 wind turbines. Visual monitoring of harbour porpoises was conducted prior to as well as during construction and operation by means of 15 aerial line transect distance sampling surveys, from 2008 to 2010. Static acoustic monitoring (SAM) with echolocation click loggers at 12 positions was performed additionally from 2008 to 2011. SAM devices were deployed between 1 and 50 km from the centre of the wind farm. During aerial surveys, 18 600 km of transect lines were covered in two survey areas (10 934 and 11 824 km²) and 1392 harbour porpoise sightings were recorded. Lowest densities were documented during the construction period in 2009. The spatial distribution pattern recorded on two aerial surveys three weeks before and exactly during pile-driving points towards a strong avoidance response within 20 km distance of the noise source. Generalized additive modelling of SAM data showed a negative impact of pile-driving on relative porpoise detection rates at eight positions at distances less than 10.8 km. Increased detection rates were found at two positions at 25 and 50 km distance suggesting that porpoises were displaced towards these positions. A pile-driving related behavioural reaction could thus be detected using SAM at a much larger distance than a pure avoidance radius would suggest. The first waiting time (interval between porpoise detections of at least 10 min), after piling started, increased with longer piling durations. A gradient in avoidance, a gradual fading of the avoidance reaction with increasing distance from the piling site, is hence most probably a product of an incomplete displacement during shorter piling events.

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A porpoise in front of four turbines of the offshore wind farm *alpha ventus* and transformer platform (montage, pictures © Ernst Shrijver)

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Effects of pile-driving on harbour porpoises (*Phocoena phocoena*) at the first offshore wind farm in Germany

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Abstract

The first offshore wind farm 'alpha ventus' in the German North Sea was constructed north east of Borkum Reef Ground approximately 45 km north off the German coast in 2008 and 2009 using percussive piling for the foundations of 12 wind turbines. Visual monitoring of harbour porpoises was conducted prior to as well as during construction and operation by means of 15 aerial line transect distance sampling surveys, from 2008 to 2010. Static acoustic monitoring (SAM) with echolocation click loggers at 12 positions was performed additionally from 2008 to 2011. SAM devices were deployed between 1 and 50 km from the centre of the wind farm. During aerial surveys, 18 600 km of transect lines were covered in two survey areas (10 934 and 11 824 km²) and 1392 harbour porpoise sightings were recorded. Lowest densities were documented during the construction period in 2009. The spatial distribution pattern recorded on two aerial surveys three weeks before and exactly during pile-driving points towards a strong avoidance response within 20 km distance of the noise source. Generalized additive modelling of SAM data showed a negative impact of pile-driving on relative porpoise detection rates at eight positions at distances less than 10.8 km. Increased detection rates were found at two positions at 25 and 50 km distance suggesting that porpoises were displaced towards these positions. A pile-driving related behavioural reaction could thus be detected using SAM at a much larger distance than a pure avoidance radius would suggest. The first *waiting time* (interval between porpoise detections of at least 10 min), after piling started, increased with longer piling durations. A gradient in avoidance, a gradual fading of the avoidance reaction with increasing distance from the piling site, is hence most probably a product of an incomplete displacement during shorter piling events.

Keywords: underwater noise effects, pile-driving, harbour porpoise, behavioural reactions, offshore wind farm, static acoustic monitoring, C-PODs, aerial surveys, North Sea



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1. Introduction

The German offshore wind power production is supposed to expand to a nominal capacity of 25 GW until 2030 (BMW 2012). This German energy policy has been developed over the last years, but was strengthened after the 2011 catastrophe at the Fukushima Daichi nuclear power plant allowing German nuclear power plants to be shut down and

decommissioned until 2022.⁶ The development of offshore wind energy is thought to play a major role within the shift of the energy mix towards renewable energies with emphasis on wind energy in general⁷. In Denmark, The Netherlands, Belgium and the UK a large number of offshore wind farms are planned or are already in operation (Breton and Moe 2009, KMPG 2010).

The first offshore wind farm in the German North Sea, the 'alpha ventus' (AV) test site was installed off the island of Borkum in the southern German Bight in 2008 and 2009. The construction and operation of this wind farm, with 12 turbines of a rated power of five MW each, was accompanied by a large number of applied research projects (RAVE—Research at Alpha VEntus) targeting operation, coordination, measurement engineering, foundation and main frame structure, systems engineering and monitoring, energy grid integration as well as ecology and safety. Ecological research focused on developing new methods, testing noise mitigation measures and evaluating the regulatory framework for conducting environmental impact assessments (EIAs), the so-called StUK 3 (Standard—Investigation of the impacts of offshore wind turbines on the marine environment, version 3; BSH 2007) of the permitting agency (German Federal Maritime and Hydrographic Agency, BSH). To evaluate whether these requirements were appropriate and lead to scientifically sound results, a comprehensive research study was conducted even at a larger scale than required by the StUK 3 and by using a wider set of methods (e.g. Krägefsky and Krone 2012, Reichert *et al* 2012).

A key species in this context is the harbour porpoise (*Phocoena phocoena*), the only resident cetacean species in German waters (Siebert *et al* 2006, Gilles *et al* 2009). Being distributed in coastal waters of the temperate northern hemisphere, the harbour porpoise is particularly vulnerable with respect to disturbance, injury, or death from anthropogenic activities, including by-catch in fisheries, prey depletion, noise (e.g. from the installation and operation of marine energy facilities), vessel traffic or habitat degradation due to chemical pollution (e.g. Siebert *et al* 1999, DeMaster *et al* 2001, Wünschmann *et al* 2001, Beineke *et al* 2005, Das *et al* 2006, Herr *et al* 2009). The most significant threat to marine mammals from offshore wind energy is most probably pile-driving impact noise (Madsen *et al* 2006). Hydraulic pile-driving was used to install the pile foundations for the 12 wind turbines and the transformer platform at AV. With each impact of the hydraulic hammer some of the energy exerted on the pile is transmitted into the water column and the seabed as an unintended by-product.

Due to the complex nature of the sound field created by a steel pile during pile-driving in shallow water (Reinhall and Dahl 2011), the source level is not an appropriate measure (Zampolli *et al* 2013), although it has been used in the past (Bailey *et al* 2010). The measured levels in different distances from pile-driving (e.g. Thomsen *et al* 2006, Nedwell *et al*

2007), however, indicate the high acoustic intensity of the impulses. Matuschek and Betke (2009) showed that emitted pressure and sound energy are correlated with pile diameter and can reach up to an L_{p-p} of 200 dB re 1 μPa and 177 dB re 1 μPa^2 s broadband sound exposure level (SEL) at 750 m distance for piles ≥ 4 m diameter (units as defined in Ainslie (2011)).

Gilles *et al* (2009) presented a risk analysis based on the results of aerial surveys and the assumption that all 18 permitted wind farms (at that time) are constructed simultaneously in the German North Sea. They concluded that 39% of the harbour porpoises in the region could show behavioural reactions in this worst case scenario, as spatial overlap exists between important areas for porpoises and areas where offshore wind farms were licensed or planned. These scenarios can only be put into perspective when other threats to porpoises, like by-catch (e.g. Kock and Benke 1996, Vinther and Larsen 2004), pollution (Jepson *et al* 2005) and other anthropogenic noise (e.g. Wright *et al* 2007, Sundermeyer *et al* 2012) are evaluated as well.

In this study the seasonal and spatial distribution of harbour porpoises were analysed by means of aerial surveys while the habitat use and behaviour were investigated with passive acoustic monitoring methods using porpoise detectors (C-PODs; Chelonia Ltd, UK) aiming to characterize the effects of pile-driving noise for a relatively small wind farm (12 turbines). Especially changes in the spatial distribution, presence patterns and the influence of seasonal variations on presence/absence of porpoises were analysed.

2. Material and methods

2.1. Study area and harbour porpoise occurrence

The study concentrated on the area of the AV test site for offshore wind turbines, located 45 km north of the island of Borkum, in the southern German North Sea (figure 1). The small wind farm (~ 4 km²) was built in an area with 30 m water depth characterized by a homogenous sediment structure mainly consisting of fine sand (Reichert *et al* 2012).

During studies conducted in the German EEZ between 2002 and 2006 the density of harbour porpoises in the southern German North Sea increased from 2004 onwards, mainly in spring (Gilles *et al* 2009). These findings are in line with observations in The Netherlands, Belgium and northern France (Kiszka *et al* 2004, Camphuysen 2011, Haelters *et al* 2011, Scheidat *et al* 2012) as well as with results of the SCANS-II survey from July 2005 (SCANS-II 2008). SCANS-II found no evidence for a change in abundance between SCANS in 1994 and SCANS-II in 2005. However, spatial modelling suggested a large shift in distribution of harbour porpoises from the northern waters to the south (Hammond *et al* 2002, 2013, SCANS-II 2008). Between 2002 and 2006 a strong seasonal variation of porpoise density was observed in the southern German North Sea (area D in Gilles *et al* 2009), with the highest density estimated for spring (March–May, 0.85 individuals km⁻² (ind. km⁻²), 95% CI: 0.45–1.72 ind. km⁻²) and the

⁶ www.bmu.de/english/transformation_of_the_energy_system/general_information/doc/48050.php, accessed: 10.01.2013.

⁷ www.bmu.de/english/transformation_of_the_energy_system/resolutions_and_measures/doc/48054.php, accessed: 10.01.2013.

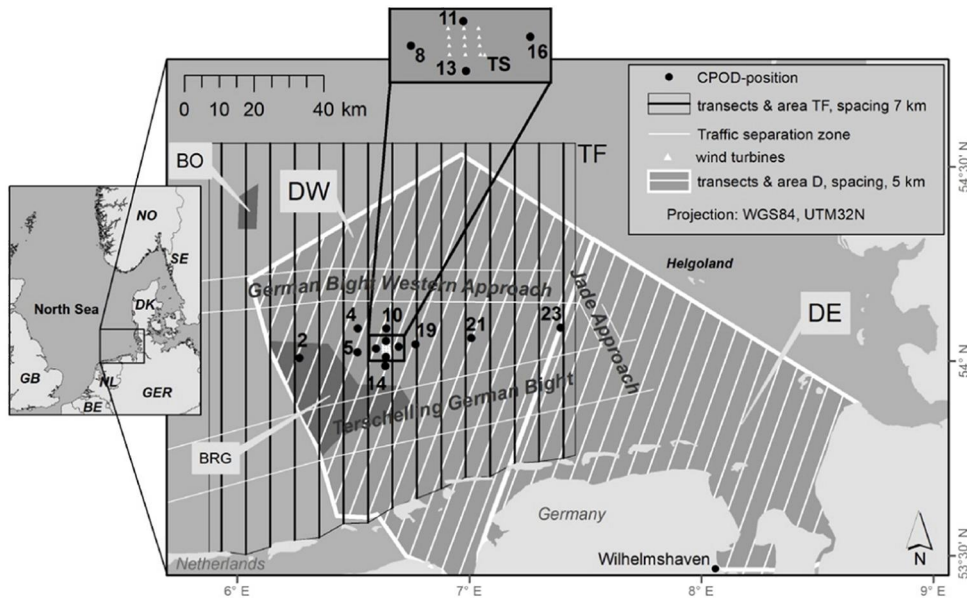


Figure 1. Study areas monitored between August 2008 and October 2010 (aerial surveys) and August 2008 and November 2011 (C-PODs; black dots). Small inset shows the location of the foundations (white triangles) and C-POD-locations closest to the wind farm (TS—transformer station, TF—aerial survey area TF, DW—western stratum of aerial survey area D, DE—eastern stratum of aerial survey area D, BRG—SCI Borkum Reef Ground, BO—BARD Offshore 1). Countries: GB—United Kingdom, NO—Norway, SE—Sweden, DK—Denmark, GER—Germany, NL—The Netherlands, BE—Belgium.

lowest density for summer (June–August, $0.17 \text{ ind. km}^{-2}$, 95% CI: $0.08\text{--}0.36 \text{ ind. km}^{-2}$). During spring of several years a hot-spot, i.e. a discrete area of particularly high harbour porpoise density, was observed at the Borkum Reef Ground (BRG) in the south-western part of the German EEZ, probably serving as one of the two key foraging areas in German waters (Gilles *et al* 2009). In The Netherlands porpoise density was shown to vary between seasons as well (Scheidat *et al* 2012): for the survey area neighbouring the southern German North Sea ('Frisian Front'), densities were estimated to be $1.02 \text{ ind. km}^{-2}$ (November 2008, 95% CI: $0.34\text{--}2.10 \text{ ind. km}^{-2}$), $0.52 \text{ ind. km}^{-2}$ (April 2009, 95% CI: $0.11\text{--}1.26 \text{ ind. km}^{-2}$) and $1.107 \text{ ind. km}^{-2}$ (March 2010, 95% CI: $0.484\text{--}2.488 \text{ ind. km}^{-2}$).

2.2. Pile-driving operations

In 2008, the transformer platform was installed by driving four piles for a jacket foundation from 18th to 25th September with a total duration of approximately 880 min. Prior to impact piling, piles were vibrated up to nine metres into the substrate for eight to 20 min and then piled with a hydraulic hammer (type Menck MHU500T) of up to 500 kJ energy (Betke and Matuschek 2011). The same procedure was used for the first six wind turbines (type Areva Wind M5000, tripod construction; three piles per foundation) from 24th April to 1st June 2009. Pile-driving operation for the Areva Wind turbines lasted for 376–802 min per foundation using 14 665–25 208 hammer strokes. The remaining piles for the other six turbine foundations (type REpower 5M, jacket

construction, four piles per foundation) were driven from 15th June to 26th August 2009 with durations of 530–561 min using 11 383–19 359 hammer strokes. Piling durations are depicted in figure 2. All pile diameters ranged between 2.4 and 2.6 m and piles were driven to approximately 30 m penetration depth (Betke and Matuschek 2011).

It has to be noted that the pile-driving of each of the first six foundations for the Areva Wind turbines (AV07-12) was conducted in less than 36 h on average while the remaining six foundations for REpower turbines (AV01-06) took up to several weeks each. The intervals between pile-driving activities, some lasting only for a few minutes, extended to a maximum of more than five days.

Two types of acoustic harassment devices (pingers and seal scarers) were used prior to piling to displace harbour porpoises and seals from the potentially harmful zone in which a temporary threshold shift (TTS) for harbour porpoises could occur (Lucke *et al* 2009). A code of conduct defined that first pingers and seal scarers were switched on simultaneously 30 min before pile-driving, however, this was not met in a systematic way during the installations. In addition, devices were switched off (1) after pile-driving for the designated foundations of the Areva Wind turbines and (2) with the beginning of the pile-driving operation of the REpower foundations. Therefore, the effect of pile-driving has to be considered as a combined effect of pile-driving and harassment, especially for stations at close range, but not for great distances (discussed in Brandt *et al* 2011).

Noise levels of pile-driving impulses were reported to vary in SEL from 154 to 175 dB re $1 \mu\text{Pa}^2 \text{ s}$ at 750 m

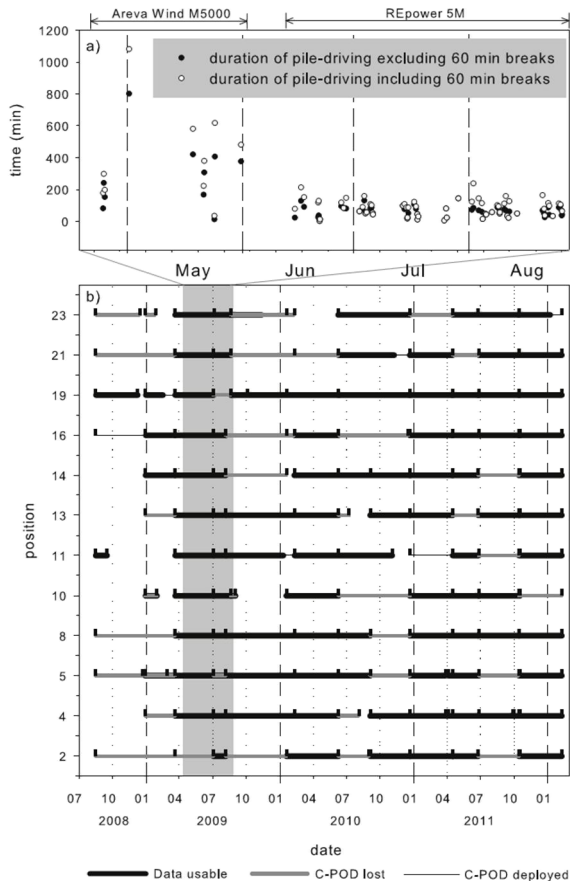


Figure 2. (a) Pile-driving times at single days in 2009, including periods with no pile-driving of up to 60 min (circles) as a measure for how long the whole process took with shorter breaks when a return of porpoises to the area is improbable and pile-driving durations only (black dots) in 2009 and (b) deployment periods of C-PODs 2008–11, ticks indicate servicing intervals.

distance (Betke and Matuschek 2011). Median SEL values of 157 dB re $1 \mu\text{Pa}^2 \text{ s}$ at 750 m distance were calculated from observations in greater distances during the test of an air bubble curtain at one of the foundations (for noise mitigation, 31st May to 1st June 2009, strongest attenuation of 10–12 dB downstream). With no such noise mitigation calculated median SEL ranged from 164 to 170 dB re $1 \mu\text{Pa}^2 \text{ s}$ in 750 m distance (Betke and Matuschek 2011). There was no apparent difference in SEL for the two foundation types. Using the empirical prognosis formula for transmission loss (TL) of Betke and Schultz-von-Glahn (2008):

$$TL = (10 + 2 \cdot \log(\text{frequency}) + (2.5 \times 10^{-8} \cdot \text{frequency} + 2 \times 10^{-5}) \cdot \text{radius}) \cdot \log(\text{radius}) \quad (1)$$

a SEL of 164–170 dB re $1 \mu\text{Pa}^2 \text{ s}$ in 750 m distance would result in SELs of 146–152 dB in 10 km; 139–145 dB in 25 km and 131–137 dB in 50 km for a typical pile-driving centre frequency of 250 Hz. Betke and Matuschek (2011)

however note that this formula most probably overestimates sound levels in distances larger than 10 km.

2.3. Aerial surveys

Dedicated aerial surveys following standard line transect distance sampling techniques (Buckland *et al* 2001) to assess density and distribution of harbour porpoises were conducted between August 2008 and October 2010. The area of the AV wind farm was covered by two survey areas (figure 1): area TF ($10\,934 \text{ km}^2$) was designed for studying the large scale effect of wind mill construction on porpoise presence as well as spatio-temporal trends. Therefore, the study area design comprised a 60 km radius around AV. The area D ($11\,824 \text{ km}^2$) was stratified in two strata (DE and DW), which could each be surveyed in one day (Gilles and Siebert 2009). Surveys in D are part of the national monitoring programme in the area of the BRG, a shallow sand bank with reef areas in 18–33 m depth of which the western part has been designated as a NATURA 2000 site (status SCI) (Krause *et al* 2006). In order to provide equal coverage within each survey area we selected a parallel transect layout in DISTANCE 5.0 (Thomas *et al* 2010) with tracks spaced seven km (area TF) and five km (area D) apart. In area TF, we placed transects in a north–south direction, parallel with water depth gradients, as transect direction should be perpendicular to the contour lines of physical or biological features (Buckland *et al* 2001). Transects in area D were placed at 60° to the shore to adapt the survey design to a north–south as well as west–east porpoise density gradient that has been described for this near shore area (Gilles *et al* 2009).

Aerial surveys were flown at 90–100 knots ($167\text{--}185 \text{ km h}^{-1}$) at an altitude of 600 ft (183 m) in a Partenavia P68, a twin-engine, high-wing aircraft equipped with two bubble windows to allow scanning directly underneath the plane. The survey team consisted of two observers, one data recorder (navigator) and the pilot. Surveys were only conducted in sea conditions Beaufort 0 to <3 and with visibilities >5 km. Environmental conditions were recorded at the beginning of each transect and updated with any change. Conditions included (1) sea state, (2) water turbidity (3) percentage of cloud cover, and for each observer side, (4) glare (angle obscured by glare and intensity of glare) and (5) the observer's subjective view of the likelihood that, given all of the conditions, they would see a harbour porpoise should one be present. These subjective conditions could be good, moderate or poor. Detailed field and analyses protocols are described in Gilles *et al* (2009). Estimation of effective strip widths and $g(0)$, following the racetrack data collection method (Hiby and Lovell 1998, Hiby 1999), allowed for precise effort correction and accounted for missed animals and sighting conditions (Scheidat *et al* 2008), taking into account both the availability and the perception bias (Marsh and Sinclair 1989, Laake *et al* 1997). All data recorded in poor sighting conditions were excluded from subsequent analysis. The total effective strip width was estimated to be 153 m (SD = 0.0452) under good conditions and 54 m (SD = 0.0162) under moderate conditions, incorporating $g(0)$

values of 0.37 and 0.14, respectively. Animal abundance was estimated using a Horvitz–Thompson-like estimator (see Scheidat *et al* (2008) for details). Coefficients of variation (CV) and 95% confidence intervals (CI) were estimated by a non-parametric bootstrap test (999 replicates) within strata, using transects as the sampling units. The subjective assessment of good and moderate conditions, assessed separately for the left and right side of the transect, was used to define sections completed under consistent conditions. For the spatial analysis in ArcGIS 9.3 a grid with a resolution of 5 × 5 km was created. The overall number of harbour porpoises (n_i) and the effectively searched area (EA_i) per grid cell i were determined, and mean density estimates were calculated by the ratio n_i/EA_i (see Gilles *et al* (2009) for more details).

2.4. Static acoustic monitoring

The C-POD is a fixed autonomous logging device designed to passively detect odontocete echolocation clicks in the frequency range between 20 and 170 kHz (www.chelonia.co.uk). It uses digital waveform characterization in an online data processing to register click events and their time of occurrence, frequency, intensity, envelope and bandwidth. Most of those parameters are derived from automated analysis of zero-crossings to save battery power and processing time compared to a full spectral wave form or frequency analysis. This information is used as input to an off-line automated train detection and classification algorithm (version 1 was used within the study). C-POD detection range may vary depending on the existing background noise level and instrument variation, within a maximum of several hundred metres. For T-PODs, the predecessor of the C-POD, it has been established that the effective detection radius for harbour porpoises can range up to the low hundred metres (Kyhne *et al* 2008, 2012). Data were automatically processed with the proprietary software C-POD.exe version 1.017 using the settings for ‘porpoise-like’ click sequences in the classes ‘Hi’ and ‘Mod’. The output format was chosen as ‘detection positive 10 min’ ($dp10min$, i.e. 10 min periods with at least one porpoise click train detection) as a relative measure for porpoise presence per day and hour ($dp10min/d$ or $dp10min/h$ respectively) and ‘waiting times’ (WT; interval length of periods of more than 10 min without detections given in minutes) as a measure for absence. First WT were defined as the WT ending with the first porpoise detection after pile-driving was commenced. Second WT was defined as the WT following first WT. First WT is used as a measure how long porpoises are displaced during and after the piling events.

12 positions equipped with C-PODs were regularly serviced every three months, from August 2008 to November 2011. C-PODs were located in an area of 80 km × 30 km stretching in the west from the Dutch border between two traffic separation zones towards the Jade Approach in the east (figure 1). Individual C-PODs were rotated between positions to distribute any error caused by instrument variation between positions. The northern and southern boundaries were set by two shipping lanes for large commercial vessels. This design of C-POD-locations allowed to determine potential

gradients in harbour porpoise presence and habitat use along an east–west transect (i.e. parallel to the coastline and depth contours) as well as from the north to the south (i.e. with decreasing water depth). All positions on the east–west transect were placed at comparable distances to the shipping lanes to eliminate bias due to shipping activity. The C-PODs (V0 and 1) were calibrated in a tank prior to deployment, between data acquisition when problems with an individual C-POD occurred, after loss/retrieval and after the study ended. The methodology is further described in Dähne *et al* (2013) and Verfuß *et al* (2010). C-PODs were deployed 10 m above the seafloor in water depths between 25.5 and 34.5 m, i.e. approximately in mid-water to eliminate potential bias by wave and sediment noise.

When referring to pile-driving within this paper in statistical analyses and results, it has to be noted that in close range of the pile-driving site the displacement of porpoises is a combined effect of acoustic harassment devices and pile-driving. Statistical analysis did not allow for a separation of these effects. Hence, we only considered pile-driving as the presumably further reaching effect (Brandt *et al* 2011) and times are only given for the conduction of pile-driving.

2.4.1. Effects of pile-driving on $dp10min/h$. Generalized additive models (GAM, Hastie and Tibshirani 1990, Wood 2006) were developed for every station independently to determine the pile-driving effect on the presence of porpoises with a focus on the comparison of hours with and without pile-driving activity at the wind farm site of the years 2008–10. Response variable was the assumed Poisson distributed $dp10min/h$, corrected for overdispersion using a quasi-GAM model and independent variables were year as a factor (F), *month* and *hour* of the day as smoothing splines (f) as well as *pile-driving* as a binary factorial variable (B), to test which factors influenced the detection rates:

$$E[dp10min/h_i] = F_{(year_i)} + B(piledriving_i) + f(hour_i) + f(month_i). \quad (2)$$

2.4.2. Duration of the effects. The second analysis was carried out to find out how long the effect of pile-driving lasted. Waiting times as a measure for absence of porpoises from the pile-driving area were tested whether they were significantly influenced by *pile-driving* using a generalized linear mixed model (GLMM, McCullagh and Nelder 1989). The first *WT* after pile-driving was used as the dependent, while *month* and *POD position* were included as random factors (*re*) to account for variation caused by seasonality and geographic position. The *duration* of pile-driving (as factor, F) was included to investigate whether duration of pile-driving affected the first WT:

$$E[firstWT_i] = F(duration_i) + re(position_i) + re(month_i). \quad (3)$$

Significance of duration was tested using a log-ratio test as well as residual and q–q plots for a quality check of the model fit (Bates *et al* 2011).

In a following step WT of 2010 and 2011 were used as baseline data, assuming that effects of the operating wind farm would be less severe than habitat exclusion during pile-driving. 2011 was the first year of full operation with less ship traffic than in 2010 (increased ship traffic in 2010 due to final work at turbines). The so-called ‘bus-paradox’ (Ito *et al* 2003, Tougaard *et al* 2009) has an influence on this analysis: long WT have a higher probability of being selected by any randomization of a single point in time (like the end of pile-driving), falling into a random period, than short WT, even if these are dominant in a frequency distribution. Hence, the mean or median of randomly selected first WT based on any point in time will have a high probability of being longer than those of second and following WTs. This is true for the first WT after pile-driving, but is also true for any randomly selected one. To take account of this paradox, we have randomly selected WT from 2010 and 2011 based on a bootstrapping procedure for each month 500 times separately to have an unbiased estimate for the first WT not affected by pile-driving. The impact of pile-driving was therefore tested by using a binomial variable *pile-driving* and modelling its impact on the first WT accounting for seasonal and geographic variation by including *month* and *position* as random factors. Months without pile-driving activity in 2009 were excluded to restrict the analysis on the season when pile-driving was conducted. All WT were tested with a GLMM assuming a Poisson distribution:

$$E[\text{firstWT}_i] = B_1(\text{piledriving}_i) + re_1(\text{position}_i) + re_2(\text{month}_i). \quad (4)$$

To take account of possible temporal correlation in the data we included an autocorrelation structure based on auto-regressive moving averages (ARMA) for residuals from the nlme package (Pinheiro *et al* 2011).

2.4.3. Displacement of harbour porpoise due to pile-driving.

In a third analysis the calculated distance (*dist* in km) from the actual pile-driving position to the individual C-POD-position was tested for significant influences on porpoise detection rates using two generalized additive mixed models (GAMMs; Lin and Zhang 1999, Wood 2006) with *dp10min* as response, *dist* as a smoother with four degrees of freedom (df) and *month* as a random factor. One model was built using only data from 10 min bins with pile-driving and the second model analysed situations without pile-driving.

$$E[\text{dp10min}_i] = f_1(\text{dist}_i) + re_1(\text{position}_i) + re_2(\text{month}_i). \quad (5)$$

The model predictions were plotted to show the displacement effect. All analysis were carried out using R 2.14.1 (R Development Core Team 2011) and the libraries lme4 0.999375-42 (Bates *et al* 2011), nlme 3.1-102 (Pinheiro *et al* 2011) and mgcv 1.7-13 (Wood 2011).

3. Results

3.1. Aerial surveys

Between 2008 and 2010, 15 dedicated aerial surveys for harbour porpoises were conducted in the area of the AV wind farm, of these three in area D (table 1). A total of 18 600 km of transect lines were surveyed and 1392 sightings of harbour porpoise groups were made on-effort. The number of sighted individuals totalled up to 1665, including 64 calves (table 1). For 10 of the 12 surveys conducted in area TF porpoise density could be estimated (figure 4), the remaining two surveys did not cover the area appropriately. In comparison to estimates in 2008 and 2010 lowest porpoise densities were estimated in 2009. As prominent seasonal differences in porpoise distribution and density were observed in the German Bight (Gilles *et al* 2009) an annual comparison of density estimates should only be investigated between same or adjacent months in different years. Results show that porpoise density in August 2009 was significantly lower than estimates in August 2008 and July 2010 (figure 4). In April 2009, at a survey date before pile-driving at AV had started, density was estimated to be 1.15 ind. km⁻² (95% CI: 0.51–2.43 ind. km⁻²), in May 2009 estimated density was lower with 0.72 ind. km⁻² (95% CI: 0.38–1.46 ind. km⁻²) and in May 2010 density was comparable to April 2009. Between 2008 and 2010 area DW was only surveyed in April, May and July 2009 and these densities were similar as estimated for TF during these months (figure 4).

In 2008 and 2009 eight flight days were conducted during periods with pile-driving activities at AV or within 48 h following pile-driving (table 1). Of these, only the survey at 1st May 2009 in area DW effectively overlapped in time with pile-driving at AV (3 h 23 min overlap; table 1) while surveying on transects in and around AV. In comparison to a survey conducted approx. one month before pile-driving had started (figure 3(a)), where porpoises were evenly distributed in the survey area and around AV, the observed distribution of porpoises at 1st May 2009 followed a different pattern. Very high porpoise densities were observed in the western and northern part of the study area (figure 3(b)) and no porpoises were visually detected in the vicinity of the construction site at AV; the nearest sighting was recorded at 20 km distance to the west of the driven pile.

During all other surveys the area close to AV (i.e., in <15 km distance) was covered before or after pile-driving took place. Surveys which covered the area around AV shortly after pile-driving ceased were conducted in area D and TF in July 2009 (table 1). It has not been possible to estimate a robust density for the survey conducted in area TF on 14th July 2009 as the study area could not be covered in total, however, the encounter rate has been low (table 1). Area DW was surveyed on 3rd July 2009 about two hours following pile-driving: no porpoises were sighted in the area close to AV and the nearest sightings were recorded at distances of 13 km in the south. Density in D for July 2009 was estimated to be 0.58 ind. km⁻² (95% CI: 0.27–1.25 ind. km⁻²) which is comparable to the estimate for area TF in August 2009 and comparably lower than densities in 2008 and 2010 (figure 4).

Table 1. Harbour porpoise aerial surveys in the area of AV and exact timing of pile-driving as well as use of harassment devices (pinger and seal scarer). Effort = survey effort in good or moderate survey conditions. Time of pile-driving includes breaks of maximum 60 min.

Survey Date	Area	Effort (km)	Sightings (no.)	Individuals (no.)	Calves (no.)	Encounter rate (sightings km ⁻¹)	Pile-driving (CEST)	Harassment (CEST)	Survey (CEST)	Time overlap with pile-driving
1	15.08.2008 TF	665	58	84	6	0.09	None	None		
	16.08.2008 TF	591	45	62	3	0.08	None	None		
	Sum	1 256	103	146	9	0.08				
2	18.09.2008 TF	951	58	67	3	0.06		None	9:56–13:13&14:54–17:34	
	19.09.2008 TF	748	32	41	3	0.04		11:50–14:30	10:09–12:46&15:05–17:11	None
	Sum	1 699	90	108	6	0.05				
3	20.03.2009 DE&DW	882	96	113	0	0.11	None	None		
	01.04.2009 DE&DW	721	18	23	0	0.02	None	None		
	Sum	1 603	114	136	0	0.07				
4	11.04.2009 TF	617	128	134	0	0.21	None	None		
	12.04.2009 TF	511	18	18	0	0.04	None	None		
	Sum	1 128	146	152	0	0.13				
5	23.04.2009 DE	849	19	19	0	0.02	None	None		
	01.05.2009 DW	995	77	89	1	0.08	01.05. 12:20–02.05. 6:22	01.05. 9:10–02.05. 4:45	9:53–12:20&14:16–17:39	3 h 23 min
	Sum	1 844	96	108	1	0.05				
6	23.05.2009 TF	844	72	75	1	0.09	21.05. 13:42–17:33 21.05. 18:38–22.05. 00:58	21.05. 11:55–22.05. 2:40	10:57–13:39&15:21–17:45	None
7	03.07.2009 DW	406	15	18	1	0.04	10:33–12:04, 20:39–23:18	4:40–5:40, 18:10–19:10	13:57–16:31 (no break)	None
	05.07.2009 DW&DE	633	45	56	5	0.07	13:45–15:33, 20:54–22:36	12:45–16:00, 19:39–20:47	10:43–13:06&15:03–18:09	30 min
	Sum	1 039	60	74	6	0.06				
8	14.07.2009 TF	714	46	54	2	0.06	07:05–08:43&18:24–20:13	4:40–15:07. 00:00	10:40–12:41&14:29–17:08	None
9	10.08.2009 TF	860	28	31	1	0.03	15:15–17:07	13:35–20:20, 23:00–12.08. 0:00	09:34–11:54&13:20–15:47	32 min
	14.08.2009 TF	669	39	48	4	0.06	0:21–0:57, 2:20–2:59	13.08. 19:50–14.08 4:00	10:59–13:38&14:53–16:23	None
	Sum	1 529	67	79	5	0.04				

Table 1. (Continued.)

Survey	Date	Area	Effort (km)	Sightings (no.)	Individuals (no.)	Calves (no.)	Encounter			Harassment (CEST)	Survey (CEST)	Time overlap with pile-driving
							rate (sightings km^{-1})	Pile-driving (CEST)	None			
10	18.09.2009	TF	575	3	3	0	0.01	None	None	None	None	
11	16.03.2010	TF	611	52	61	0	0.09	None	None	None	None	
12	11.05.2010	TF	810	59	66	0	0.07	None	None	None	None	
	14.05.2010	TF	724	119	133	1	0.16	None	None	None	None	
	Sum		1 534	178	199	1	0.12					
13	05.06.2010	TF	830	110	148	18	0.13	None	None	None	None	
	09.06.2010	TF	474	22	28	3	0.05	None	None	None	None	
	Sum		1 304	132	176	21	0.10					
14	10.07.2010	TF	777	114	145	7	0.15	None	None	None	None	
	23.07.2010	TF	716	45	50	2	0.06	None	None	None	None	
	Sum		1 493	159	195	9	0.11					
15	12.10.2010	TF	586	3	6	1	0.01	None	None	None	None	
	17.10.2010	TF	841	71	93	2	0.08	None	None	None	None	
	Sum		1 427	74	99	3	0.05					
	Σ	TF	14 114	1122	1347	57	0.08					
	Σ	D	4 486	270	318	7	0.06					
	Σ		18 600	1392	1665	64	0.07					

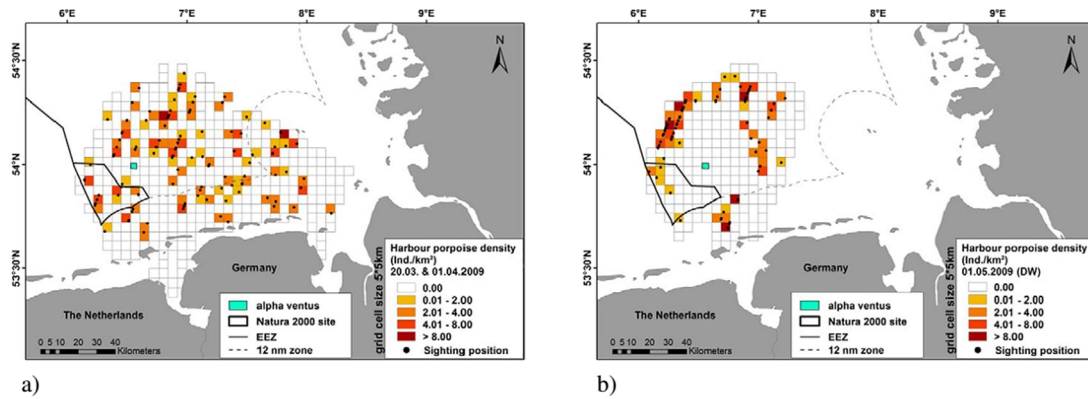


Figure 3. Spatial distribution of harbour porpoise density and sightings. (a) Pre-pile-driving in March/April 2009 and (b) during pile-driving in DW (1st May 2009; DE was not surveyed during pile-driving at that particular time). Projection: WGS84, UTM Zone 32N.

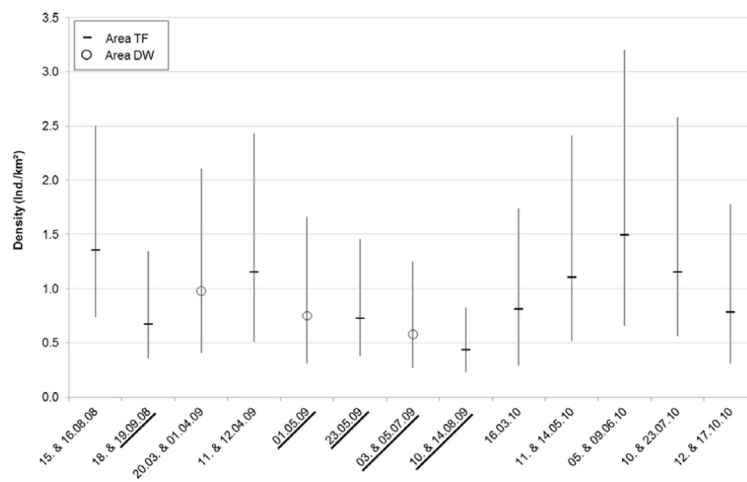


Figure 4. Estimated density of harbour porpoise per survey in the study areas TF and DW. Error bars show 95% confidence limits. Area TF is indicated by short dashes for the estimated density, area DW is represented by open circles. Dates of surveys conducted during pile-driving or within 48 h following pile-driving at AV are underlined in black.

3.2. Static acoustic monitoring

Devices had a mean 50% peak–peak detection threshold (received level where 50% of sent out clicks were detected by the device in a test tank) of 117.3 ± 2.6 (standard deviation) dB re $1 \mu\text{Pa}$ at 130 kHz. For more details on the methodology please see Dähne *et al* (2013).

3.2.1. Effects of pile-driving on harbour porpoise presence ($dp10min/h$). $dp10min/h$ showed a strong seasonal variation among all stations (e.g. station 11 and 19 in figure 5). Detection rates peaked from September to January and lows were encountered from late April to early August. Detection rates in the latter months in 2009 were close to zero. In 2010 and 2011 higher detection rates were encountered when compared to 2009. Construction work was unintentionally carried out during a period of low detection rates potentially caused by a combination of seasonal variation and pile-driving

effects. The $dp10min/h$ varied geographically, with less detections in closer vicinity of the wind farm and increased detection rates towards BRG.

Data analysis with GAMs depicted that not all stations showed the same temporal variation in $dp10min/h$. Eight stations within 10.8 km of the wind farm (except stations 10 and 2) showed a negative impact of hours when pile-driving was conducted in comparison to hours without pile-driving (table 2). Two stations showed significantly more detections during hours with pile-driving. These stations were deployed in a distance of about 25 and 50 km from the construction site (stations 21 and 23). The variable *month* had a significant impact in all models, while *year* was not significant at stations 2 and 23, and *hour* was not significant at station 19. Pronounced diurnal and seasonal variations were detected between stations (figure 6). Explained deviances varied from 3.84 to 20.07% showing that most of the variation cannot be explained by yearly, seasonal and diurnal variation in combination with pile-driving alone.

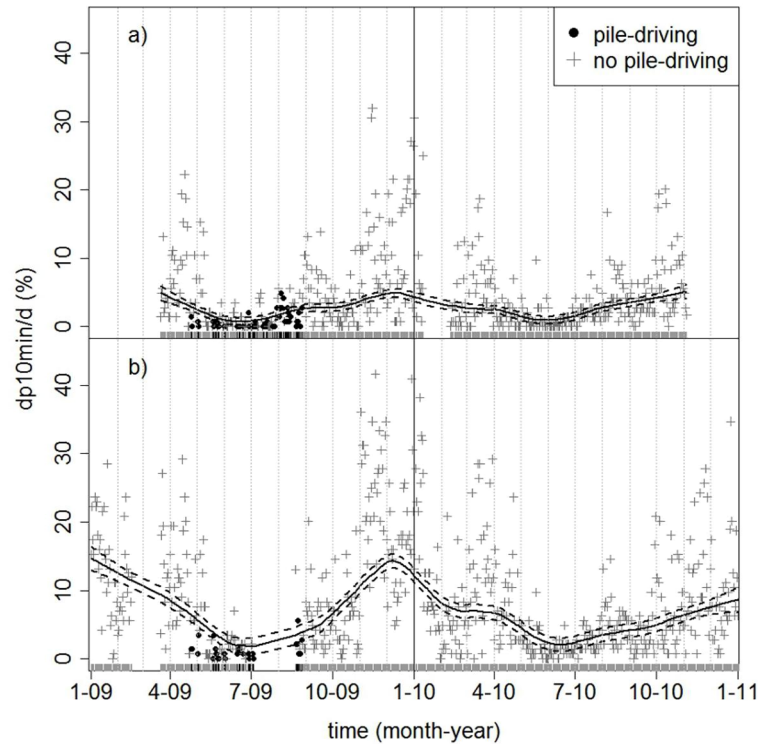


Figure 5. Detection positive 10 min periods per day ($dp10min/d$) for 2009 and 2010 at (a) station 11 and (b) station 19. Days with pile-driving are marked with black dots, days without pile-driving with grey crosses. The black line represents a smoothing spline with 95% confidence limits (dashed lines). Ticks below the plot represent available data points.

Table 2. Summary of the GAM-models, the intercept represents the modelled mean of the $dp10min/h$ and the intercept of singular variables. n.s. = not significant, n = number of samples, Expl. dev. = explained deviance.

Position	Distance to piling site min-max (km)	n	Intercept	Intercept pile-driving	Effect	p pile-driving	p year	p month	p hour	Expl. dev. (%)
2	25.2–26	6 848	0.99	n.s.	n.s.	n.s.	n.s.	<0.001	<0.001	8.23
4	8–10.8	13 315	0.88	–0.42	–	<0.001	<0.001	<0.001	0.025	10.87
5	7.4–9.8	12 039	–0.66	–1.24	–	<0.001	<0.001	<0.001	<0.001	17.08
8	2.3–4.6	12 838	0.42	–1.36	–	<0.001	<0.001	<0.001	<0.001	10.54
10	3.0–4.2	5 602	1.08	–0.61	n.s.	n.s.	<0.001	<0.001	<0.001	19.84
11	0.5–2.5	14 226	0.00	–1.16	–	<0.001	<0.001	<0.001	<0.001	13.92
13	2.3–4.7	12 823	–0.55	–0.86	–	<0.001	<0.001	<0.001	<0.001	6.46
14	4.5–7.0	12 846	2.22	–0.81	–	<0.001	<0.001	<0.001	<0.001	8.90
16	2.5–4.5	11 286	0.76	–1.67	–	<0.001	<0.001	<0.001	0.003	20.07
19	7.2–9.2	14 970	1.28	–1.51	–	<0.001	<0.001	<0.001	0.095	16.81
21	23–25	7 283	–1.81	0.25	+	0.005	<0.001	<0.001	<0.001	13.81
23	48.7–50.5	9 406	–0.62	–0.54	+	<0.001	n.s.	<0.001	<0.001	3.84

The C-POD data showed an increase in harbour porpoise presence towards the end of the piling period in August/September 2009, i.e. during the installation of the last three foundations (figure 5).

3.2.2. Duration of the displacement effect. WT strongly varied throughout the seasons with elevated WT between April and August in all years (figure 7). The first WT between successive harbour porpoise detections during pile-driving, including mitigation in 2008 and 2009, showed median values

ranging from 81 min (position 2) to 1444 min (position 11) with a median of 1008 min (for all positions) and a maximum of 8468 min (position 13) (figure 7). Only a single porpoise detection was registered during pile-driving operation on position 11 at 1.03 km distance from the piling site on 29th July 2009 from 7:52 to 8:12 CEST; pile-driving started that day at 06:06 and lasted until 08:30. Acoustic harassment devices were operating from 01:30 to 08:45 that day. All other detections at the four closest C-PODs were in distances greater than 1.7 km from pile-driving. There is a general

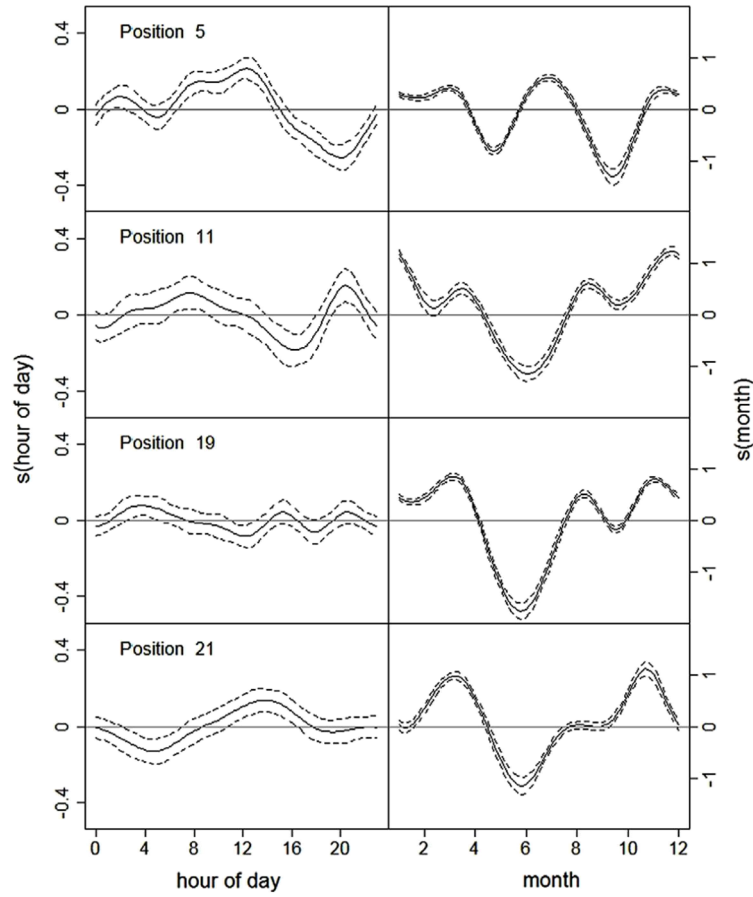


Figure 6. Smoothing splines (s) of generalized additive modelling at stations (a) 5, (b) 11, (c) 19, (d) 21 over the years 2008–2010. Significance of the results is displayed in table 2.

trend towards lower first WT close to the surrounding of the construction site (i.e. <3 km) after consecutive, but shorter pile-driving sequences during the installation period of all 12 turbine foundations in summer 2009 (figure 7).

Mean WT in the study area at different positions were generally comparable ranging from 46 to 60 min, except for stations close to BRG (2, 5 and 14) showing lower WT (median of 34, 35 and 38 min, respectively) and position 23 with slightly elevated median WT of 67 min (figure 7). These stations and station 23 showed the least effect by pile-driving activity on the first WT. Second WT were generally more randomly distributed in all WT (figure 7). The linear mixed effects models showed significant effects of *pile-driving* ($p < 2.2 \times 10^{-16}$, correlation of fixed effects: -0.048 , $t = 12.8385$) and *duration* ($p < 2.2 \times 10^{-16}$, correlation of fixed effects: -0.008 , $z = 33.61$) in their respective log-ratio tests. With increased duration of pile-driving the WT also increased, even though the effect of seasonality has been considered within the model. Hence, the effect of *pile-driving* can only be considered when *duration* of pile-driving is taken into account. First WT increased to a median of 16.5 h during pile-driving within 25 km of the source. This represents a

modelled increase of first WT compared to WT chosen by a randomized date/time from 2010 and 2011 of 9.9 h.

3.2.3. Displacement of harbour porpoise due to pile-driving.

The GAMMs constructed from only *dp10min* with or without pile-driving showed a clear effect of the two random factors *month* and *position*, as well as *dist*. Model predictions had a reduced probability of detection during pile-driving at all stations within a radius of 10.8 km as the two model predictions (with/without pile-driving) do not overlap (figure 8). There is a data gap between 10.8 and 23 km. A certain amount of overlap exists for positions with distances larger than 20 km from AV. It must be noted that the model for pile-driving predicted zero or nearly zero values even in distances up to 50 km from the source.

4. Discussion

Two large scale surveys in European waters (SCANS and SCANS-II) showed that harbour porpoise distribution can shift within a decade, possibly due to a change in prey occurrence in the North Sea (Hammond *et al* 2002, SCANS-II

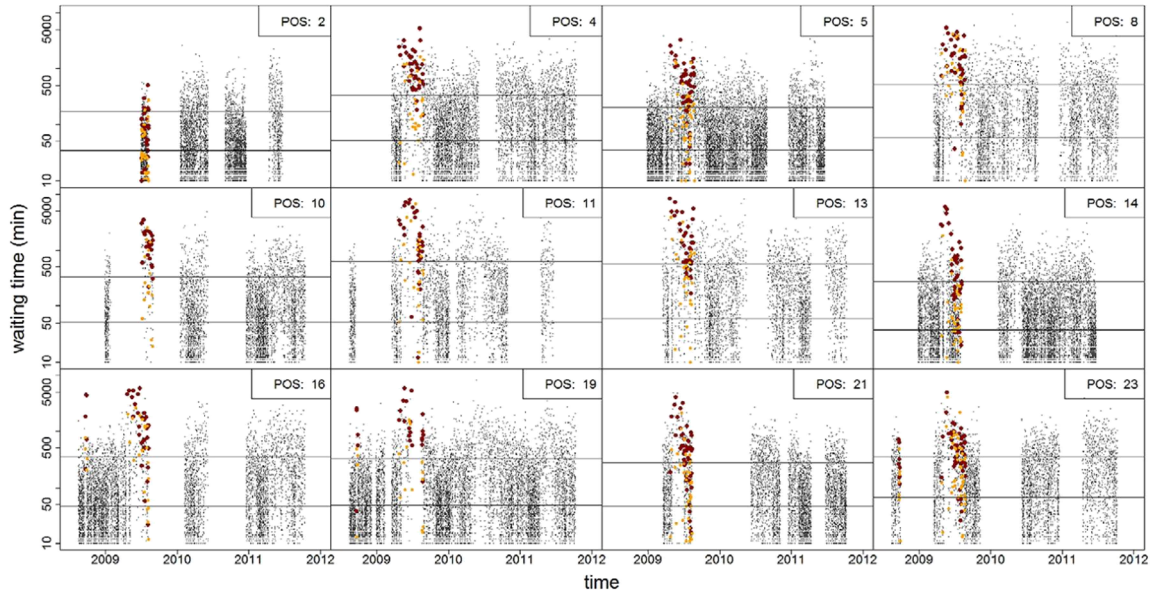


Figure 7. Analysis of waiting times (WT) for each C-POD-position. Grey dots mark WT without pile-driving and red dots mark 1st WT after pile-driving was commenced, orange dots are 2nd WT after pile-driving. The horizontal black line and grey line indicate respectively the median and the median + standard deviation of all WT at that position. Y-axis is log scaled.

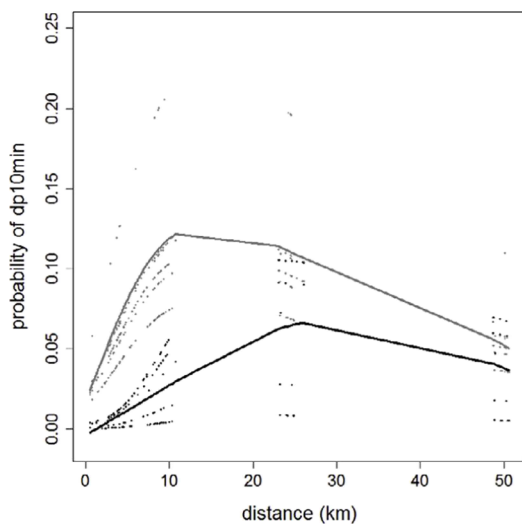


Figure 8. Behavioural changes at different distances to pile-driving analysed with two GAMMS. Grey: GAMM constructed from the *dp10min* without pile-driving; distance was calculated towards the centre of the wind farm. Black: *dp10min* for days when pile-driving was conducted; distance was calculated for each piling event individually. The x-axis displays the calculated distance to the pile-driving operation; the y-axis depicts predicted values of the probability to detect a positive *dp10min*. Lines represent a smoothing spline with 5 df for each model.

2008). Dedicated visual surveys are indispensable for robust abundance estimation within a predefined study area, but it is challenging to detect changes in distribution and density to a degree, that would be helpful for small scale wind farm impact

studies. Hence, these survey methods have to be combined for instance with static acoustic monitoring, that proved to be effective within environmental impact studies on small scales (Carstensen *et al* 2006, Tougaard *et al* 2009, Brandt *et al* 2011).

4.1. Aerial surveys

The survey conducted during pile-driving on 1st May 2009 showed a possible strong avoidance reaction of harbour porpoise during construction. Three circumstances have to be considered: (a) acoustic harassment devices were switched on for a long time prior pile-driving; (b) pile-driving activities lasted for a prolonged time (1st May 2009: 9.5 h pure pile-driving time, 11.5 h including breaks for up to 60 min, when a return of porpoises to the area is at least uncertain); (c) logistics: the exact timing of the survey fitted to pile-driving activities. In order to conduct successful and representative visual surveys for harbour porpoises it is of uttermost importance to survey in good weather periods, with a calm sea surface and good visibility (Gilles *et al* 2009). Therefore, not all surveys could be timed to fit perfectly well to actual pile-driving activities or were conducted during shorter pile-driving sequences. Lower densities were estimated for 2009, compared to 2008 and 2010. This change in porpoise abundance cannot be solely attributed to the pile-driving activities at AV as other factors influencing porpoise presence, like e.g. prey availability or other anthropogenic activities need to be considered as well within this survey area. However, the event on 1st May 2009 shows that avoidance can be documented by aerial surveys, representing a snapshot method, under certain

conditions. The pronounced difference in the distribution between the surveys before (March/early April 2009) and during construction (May 2009) is clearly indicating that the first construction activities at the AV test field had an influence on porpoise distribution. The most sensible explanation for the documented effects is a reaction to the sound emissions as no other sensory input would last over such vast distances. Moreover, harbour porpoises have been shown to have a very sensitive hearing and react to underwater sound (Andersen 1970, Kastelein *et al* 2002, 2010). Lucke *et al* (2009) showed that aversive behavioural reactions of a captive harbour porpoise were initiated at a received SEL of >145 dB re $1 \mu\text{Pa}^2 \text{ s}$ which corresponds to a distance of >10 km ($146\text{--}152$ dB re $1 \mu\text{Pa}^2 \text{ s}$ calculated SEL) and <25 km ($139\text{--}145$ dB re $1 \mu\text{Pa}^2 \text{ s}$ calculated SEL) around the AV pile-driving site coinciding approximately with the observed avoidance distance of porpoises detected during the aerial survey on 1st May 2009, when only three porpoises were sighted within 25 km from the pile-driving operation. Calculated SELs are probably overestimates (Betke and Matuschek 2011). Hence, a displacement may be caused by smaller SELs than reported here. Therefore, future studies should include the use of automated noise loggers to have a better basis for evaluation of the effects, especially in distances larger than 10 km.

The effect of deterrence devices and pile-driving must be considered as a combined effect for stations close to the source, as deterrence devices were switched on and off during and before pile-driving without a clear pattern, which should be implemented into sophisticated modelling approaches.

4.2. Static acoustic monitoring

The avoidance effect documented by the aerial survey on 1st May 2009 is confirmed in its spatial extent by the C-POD data which showed a significant negative correlation between pile-driving activity and the presence of harbour porpoises over a range of at least 10 km from the wind farm site. This effect is gradually decreasing towards 50 km as the farthest distance where C-PODs were deployed. WT increased up to a maximum of 8468 min (~ 6 days, station 13, distance 1.7 km) showing that the pile-driving impact can last for a long time during periods of generally low porpoise detection rates. Additive mixed modelling allowed to confirm that seasonality, diurnal rhythm, as well as pile-driving influence porpoise distribution and habitat use. The higher detection rates at 25 and 50 km distance showed that porpoises were possibly displaced towards these stations. This implies that a behavioural reaction cannot be defined by a potential displacement radius alone, but could reach further as an increase in detection rates can also be seen as a behavioural reaction. It is not clear to us whether the longer piling events led to a complete spatial displacement in terms of a stationary situation, where in- and outflow of porpoise into the affected area are balanced, as first WT and duration of pile-driving were correlated. Hence, it could be that porpoises were not completely displaced to a range where they would naturally stop to further move away. If that is true then porpoises

were probably exposed to multiple sound events above their behavioural reaction threshold over long time periods up to distances of 50 km. Sound propagation effects lead to a high uncertainty of predicted SELs by formula (1) in great distances. As a consequence, future research should also focus on developing applicable prediction models and measuring the noise level directly at the C-POD.

The increase in harbour porpoise detection rates in late summer 2009 cannot be unequivocally explained—it could either be due to seasonal variation caused by a high abundance of preferred prey, disturbance or deteriorating conditions in adjacent areas, habituation or other factors (each in combination). However, the detection of a harbour porpoise click train close to on-going pile-driving gives reasons for severe concern about the acoustic exposure of these animals to the piling impulses. It took on average more than 15 000 piling strikes to install each turbine (a tripod or jacket construction installed on three to four pile foundations) with SELs calculated of up to 175 dB re $1 \mu\text{Pa}^2 \text{ s}$ in 750 m distance (Betke and Matuschek 2011). Each individual that returned to the construction site and remained during the pile-driving period was consequently exposed to a high number of strikes at considerable noise levels, thereby accumulating the acoustic energy in its hearing system. A limit for temporary threshold shift of received L_{p-p} of 200 dB re $1 \mu\text{Pa}/\text{SEL}$ of 164 dB re $1 \mu\text{Pa}^2 \text{ s}$ was determined for a harbour porpoise in captivity for an exposure to single impulses (Lucke *et al* 2009). Consequently, it is one hypothesis that in the case of regular pile-driving without noise mitigation measures a number of animals suffered a temporary auditory impairment. The results of the study cannot validate whether the same individuals were exposed multiple times, or if the ecological and/or prey preferences led to an inflow of acoustically unaffected animals. Results from the North Sea (Tougaard *et al* 2009, Brandt *et al* 2011) showed that the effect of the construction of a wind farm was short-term, while results from the Baltic Sea (Carstensen *et al* 2006) suggested a possible longer lasting reaction. When considering the health status of these animals being already under pressure by pollution, habitat deterioration due to (over-)fishing, non-target by-catch and other noise sources, it is very probable, that at least some animals cannot react sufficiently fast. For instance swimming speeds are naturally reduced for mother-calf pairs. This could explain why one detection occurred at one kilometre from the wind farm during pile-driving. Multiple displacements could lead to elevated stress levels in addition to a possible hearing impairment.

Along with the possible impact of pile-driving on the auditory system and physiological consequences, a temporal displacement from a potentially optimal habitat needs to be considered. Multiple simultaneous construction activities are for instance planned within close vicinity of the Natura 2000 site 'Sylt Outer Reef' where a large proportion of the local harbour porpoise population reproduces (Gilles *et al* 2009, 2011). This could potentially lead to a reduction in fitness of individual animals, and due to possible disturbance during feeding and mating, to a reduction of fitness of the population in places of high abundance where prey availability, but also the competition for food, is higher.

The main challenge of future research will be to determine whether the construction, operation and decommissioning of offshore wind farms has population level effects for harbour porpoises or not (NRC 2005). To achieve such insight, it will be necessary to use all available methodologies within a coordinated framework as presented here. Right now all studies on effects of wind farms on porpoises are mainly based on measurements with stationary moored acoustic data loggers. While this methodology allows for a very detailed analysis of short-term reactions (Carstensen *et al* 2006, Tougaard *et al* 2009, Brandt *et al* 2011) as well as long-term changes in habitat use (Scheidat *et al* 2011) it is not yet clear how to link those results to the status of the population and what would be the influence of a simultaneous construction of a number of wind farms on porpoise distribution, habitat use, health and reproductive success. It may be necessary for future studies to involve additional large scale aerial surveys over long periods before, during and after pile-driving to establish such a link.

5. Conclusion

Using large scale aerial surveys and extensive SAM it was possible to analyse the effects of pile-driving in more detail than previously reported. Pile-driving SELs between 139–145 (25 km) and 146–152 (10 km) dB re $1 \mu\text{Pa}^2 \text{ s}$ most probably lead to a displacement of harbour porpoises, which could be seen in one aerial survey perfectly timed to pile-driving as well as on the C-POD data. These SELs are most probably overestimates indicating that the behavioural reaction threshold of harbour porpoises towards pile-driving sounds is lower. Within 25 km radius the median WT changed to 16.85 h during pile-driving. A major outcome is that the duration of pile-driving had a large impact on the WT with longer pile-driving durations leading to a longer displacement. Future research should be aimed at defining the consequences on the population level. This concerns on one hand multiple exposures in close vicinity of pile-driving during shorter pile-driving times and breaks including a potentially decreased fitness due to multiple flight reactions and energy expenditure. On the other hand a prolonged absence from the pile-driving site can result in a considerable temporal habitat loss. It is unclear which of those possibilities is potentially more threatening. The effect of noise mitigation measures like air bubble curtains and ‘Hydro Sound Dampers’ tested for instance by Würsig *et al* (2000), Lucke *et al* (2011) and Wilke *et al* (2012) will most probably have a reduction effect on displacements if used continuously during pile-driving.

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6 Air bubble curtains - an efficient method for noise mitigation in offshore construction work?

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Percussive pile-driving operations for the erection of offshore wind farms will continue for the next decades in the German North Sea. Biota like harbor porpoise *Phocoena phocoena* are likely to be displaced, or even temporary or permanently injured by the loud piling events. Noise mitigation strategies to prevent more serious effects of impulsive sounds are still under development. One such strategy, air bubble curtains, a simple and applicable method was tested in this study for its efficacy to attenuate under water noise using trials in a test tank and in a confined harbor using underwater loud speakers. We investigated acoustic attenuation properties of the bubble curtain for different spacings of air nozzles, nozzle diameter, overpressure, and air flow rates. The dominant factors in noise reduction were air flow rate and partly the spacing of nozzles on the air hose. In addition, trials demonstrated that bubble curtains show a high potential to attenuate under water sounds, with minimum attenuation rates (during field trials) of 15 to 48.3 dB (mean 36.5 dB) depending on the frequency tested. These values have to be regarded as minimum attenuation rates, as the bubble curtain self noise at high flow rates prevented a reliable detection of the output signal.

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Picture of the test tank bubble curtain through ‘the half sphere’ (© Michael Dähne & Andreas Ruser, ITAW)

6.1 Introduction

Human contributions to underwater noise increased significantly during the last decades (e.g. McDonald et al., 2006; Slabbekoorn et al., 2010). Ship traffic (e.g. Hatch et al., 2008; Hildebrand, 2009), underwater explosions through military actions and ordnance removal (reviewed in Koschinski and Kock, 2009), seismic exploration (e.g. Di Iorio & Clark, 2009), mid and long range sonar (Hildebrand, 2009), acoustic harassment devices (Brandt et al., 2012; Hildebrand, 2009; Johnston, 2002) as well as offshore construction work (Brandt et al., 2011; Carstensen et al., 2006; Dähne et al., 2013; Tougaard et al., 2009) have potentially detrimental effects on marine mammals and other biota due to the radiated noise. Sound levels from some of these sound sources cannot be easily attenuated to protect biota, but for ordnance removal and offshore construction work air bubble curtains (ABC) may be a solution to prevent negative effects on marine mammal hearing (Koschinski and Kock, 2009; Lucke et al., 2011; Würsig et al., 2000). At sea offshore construction work is likely to continue for the next few decades due to the developing offshore wind farm industry. For Germany currently over 60 projects have either been already permitted to be built or are in the licensing procedure. With each project planning to build up to 80 generators during the construction phase, which may last from a few months to multiple years, it becomes increasingly important to use noise mitigation measures to lower sound emissions at sea. In Germany three species of marine mammals are of special relevance: harbor porpoise (*Phocoena phocoena*), harbor seals (*Phoca vitulina*) and gray seals (*Halichoerus grypus*).

The effects of noise on marine mammals can be manifold and range from audibility (technically not an effect) to masking effects, behavioral reactions like e.g. increased respiratory rate and displacement, temporary or permanent threshold shifts (TTS or PTS), other organ injuries and death (Richardsen et al. 1995). The German permitting authority for offshore wind farms (Federal Maritime and Hydrographic Agency) is currently using a precautionary measure of an SEL of 160 dB re $\mu\text{Pa}^2\text{s}$ and L_p of 190 dB re μPa in 750 m distance as an obligation for noisy construction work as a single exposure criterion. These values are loosely based on an experiment on a harbor porpoise in captivity to find the threshold where a temporary shift in hearing sensitivity due to an impulsive fatiguing noise source (airgun) was recorded for a harbor porpoise at an SEL₉₀ of 164.3 dB re $\mu\text{Pa}^2\text{s}$ and L_{p-p} of 199.3 dB re μPa (Lucke et al., 2009).

Possibilities to mitigate the potential effects of pile-driving on biota are to use a) *less noisy installation techniques* like heavy and drilled foundation or b) *noise mitigation at the source* to attenuate emitted underwater sound levels. These two mitigation strategies can be termed 'noise mitigation' and will potentially mitigate both the physiological damage, in terms of TTS, PTS, injury and death, as well as the behavioural and stress reaction. Mitigation of the effects of pile-driving can also be achieved by using c) *acoustic harassment devices* (Brandt et al., 2013, 2012; Johnston, 2002; Olesiuk et al., 2002) to displace animals prior to piling from a potentially detrimental radius. This strategy can only mitigate potential physiological effects. The same holds true for d) *marine mammal observers* scanning the area to stop piling work when animals are seen in a potentially detrimental radius. The latter two cannot be termed 'noise mitigation' as they do not mitigate noise and in fact acoustic harassment devices increase noise levels and have

potentially farther reaching displacement effects than necessary (Brandt et al., 2012, 2013).

The principle behind the attenuation effect of the most advanced noise mitigation system in water, the air bubble curtain, is the impedance mismatch between air and water resulting in scattering of sound energy and resonances of air bubbles depending on the frequency of incident energy and bubble size (Medwin, 2005). Significant work has already been carried out to describe theoretical relationships of backscatter from uniform and differently sized gas bubbles (Feuillade and Werby, 1994; Feuillade, 1995). Studies of attenuation efficiency have also been carried out by Rustemeier and colleagues. They focused on simulating idealized (spherical) bubbles to estimate which bubble size would result in the best attenuation efficiency (Rustemeier et al., 2012). However in real world conditions bubbles do not behave like ideal spherical bubbles of singular size, but form a mixture of differently formed bubbles of varying sizes more similar to a two phase medium described by Medwin (Medwin, 2005). At sea ascending bubbles grow in size due to decreasing ambient pressure, split due to current movements, collide and unite with other bubbles and change shape constantly. Bubble distribution as well as bubble size will hence vary with the bubble curtain configuration and water conditions having ever changing 'holes' or 'gaps' due to current and wave motion. Field experiments are thus necessary to investigate whether a bubble curtain can effectively attenuate under water noise.

Different foundation types (monopiles or jacket foundations) require adapted noise mitigation methods: ready-to-use systems which are easy to deploy, cost effective and usable for at sea conditions are just becoming available at the moment. Any potential system must not significantly increase operational time during piling, since any increase in ship days will result in elevated costs, potentially reducing the chance that ABC's are seen as a viable mitigation strategy.

A useful system must attenuate impact noise under strong current conditions (over 1 m/s) and in variable water depths (~10 – 40 m). One concept in an advanced development stage is the so called 'large bubble curtain' (Koschinski and Lüdemann, 2011, Würsig et al., 2000) being one long hose placed on the sea floor with a large radius (~50 - 100 m). This large radius allows rising bubbles to drift in high currents whilst still surrounding the pile. The use of such a system has been described by Diederichs et al., 2013 as being capable of effectively reducing the temporal and spatial exclusion of porpoises during offshore pile-driving. Other noise mitigation systems have been compiled and evaluated in Koschinski and Lüdemann (2011) and Nehls et al. (2007). Five of these were tested in Germany on a demonstration pile in the Kiel Bight (Wilke et al., 2012) resulting in reductions in sound exposure levels (SEL) of 7 to 9 dB re $\mu\text{Pa}^2\text{s}$. The used systems (all in Wilke et al., 2012) included stacked air bubble curtains (Little Bubble Curtain, LBC, Weyres, Germany), which emit air bubbles at different depths within the water column partially reducing the risk of bubble drifting in the current and not surrounding the pile. In addition, double pipe systems excavating the water within a double wall to be replaced by air or a two phase medium of air and water (Noise Mitigation Screen, NMS, IHC, The Netherlands and Weyres BeKa Jacket, Weyres, Germany), as well as a Fire Hose System (FHS, Menck, Germany) consisting of multiple layers of fire hoses forming a closed air filled space directly on the pile, were tested in

these experiments. The Hydro Sound Damper (HSD, TU Braunschweig and Karl-Heinz Elmer, Germany) replaces ascending air bubbles by fixed air filled cavities in plastic bodies.

Multiple projects have already used unconfined ABC's for noise mitigation in the United States (Laughlin 2005, 2007, Rickman, 2000), Hong Kong (Würsig et al., 2000) and Denmark (Lucke et al., 2011) with differing sound attenuation results depending on air volumes used (Fig. 6-1).

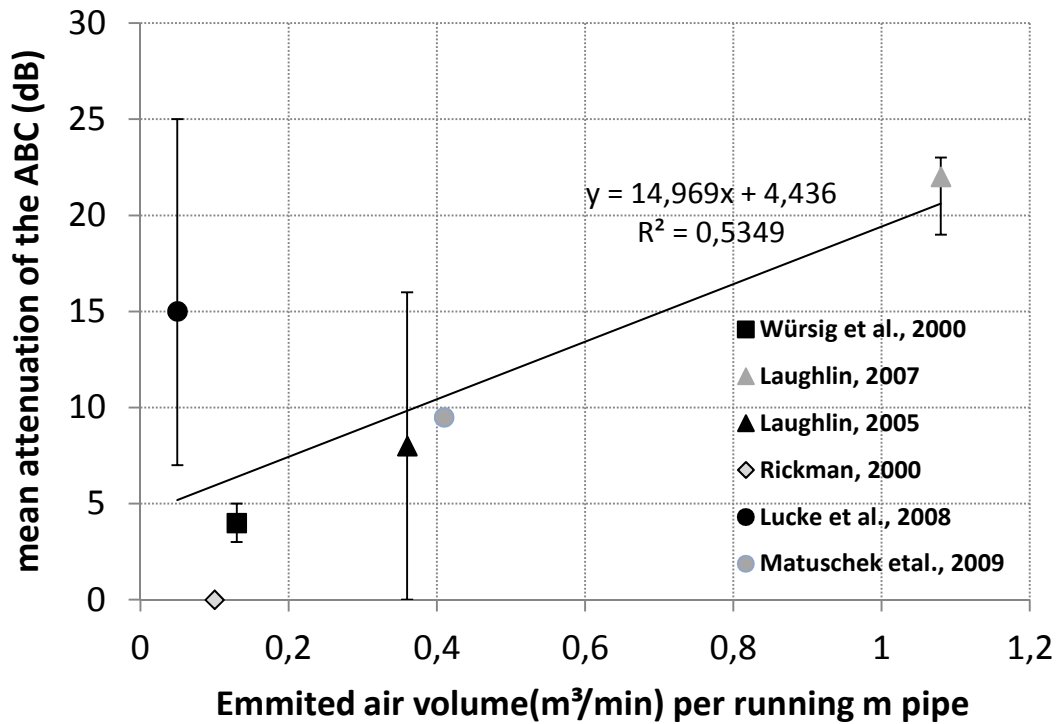


Fig. 6-1 Mean attenuation of air bubble curtain (ABC) systems vs. emitted air volume per running meter pipe in previous studies (Laughlin, 2005, 2007; Lucke et al., 2011; Rickman, 2000; Würsig et al., 2000); dB - deciBel. Attenuation rates varied for different measures of sound in Lucke et al. (2011), but were only reported as reduction in rms or peak sound pressure levels within the other studies. Water depth may have been another influencing factor, amongst others, with ~25 m (Matuschek et al., 2009), ~ 4 m (Lucke et al., 2011) and all other studies ranging between 7 and 13 m. Error bars represent minimum/maximum reported attenuation levels.

There seems to be a loose correlation between emitted air volume and the mean attenuation of these systems. Probable explanations for these differences are variable current conditions during deployment and different physical properties during these studies (marine environment, harbor or river, sediment type, sea state etc.), but there is also a wide variation of pipe design with respect to nozzle diameters and nozzle positioning on the pipe (see Fig. 6-1).

One of the studies conducted to date in particular (Lucke et al., 2011) achieved a much better noise attenuation, than the others, using relatively low emitted air volumes indicating that better efficiency of air bubble curtains may be achieved using a specific

nozzle layout, air pressure and air volume. It must be noted, however, that also the water depth during these trials was much lower (~4 m at the porpoise pool) than for the other studies in Fig. 6-1 and there were also differences regarding the pile type (wooden piles vs. steel piles).

Two main fields of interest therefore remain: testing different configurations of pipe design under controlled conditions to reduce the rental costs for expensive oil-free compressors and designing a modular air bubble curtain for field exercises. Measurements in a test tank were conducted to estimate parameters for a stacked bubble curtain system. An optimized system was tested in Kiel harbor in the Baltic Sea. The main goal of the study was to demonstrate a noise attenuation system that does not adversely interfere with the pile driving process and is easy to use and deployable in realistic ocean conditions in a short time period to keep costs at a minimum. The system was supposed to be adaptable to different water depth and current conditions and to allow typical pile-driving noise to comply with the German precautionary value of an SEL of 160 dB re $\mu\text{Pa}^2\text{s}$ in 750 m distance.

6.2 Material and methods

6.2.1 Tank trials

Trials to determine the final pipe design for field trials were carried out in a 4.78 x 4.04 x 2.00 m test tank (inside dimensions) with both visual as well as acoustic methods. Main parameters for the tests are summarized in Table 6-1.

Table 6-1 Parameters for testing of the bubble curtain in the test tank. Parameters were chosen based on the literature (Laughlin, 2005, 2007; Lucke et al., 2011; Matuschek et al., 2009, Rickman, 2000; Würsig et al., 2000). Rings for acoustic trials were based on results of visual trials.

Parameter tested	Visual trials	Acoustic trials		
		R1	R2	R3
Nozzle diameter (d)	1; 1.5; 2; 2.5; 3 mm	1 mm	1.5 mm	alternating 1 and 1.5 mm
Distance between nozzles (s)	3.25; 7.5; 15; 30 cm	7.5 cm	7.5 cm	3.25 cm
Overpressure		2 and 5 bar		
Air flow rate	variable between <8 m ³ /h to 100 m ³ /h	0, 10, 20, 30 40 m ³ /h		

6.2.1.1 Visual trials

Two perpendicularly fixed cameras were used to find the best compromise between overpressure (the air pressure at the first nozzle), air flow rate and the spacing, diameter and positioning of air nozzles on the pipe in terms of homogeneity and closure of the bubble curtain. Tube sections of 80 cm length with an effective test length of 60 cm were used to test nozzle diameters of 1, 1.5, 2, 2.5 and 3 mm with spacing of 3.25, 7.5, 15 and 30 cm. Nozzle diameters were chosen based on readily available tools. Two sets of tests were performed with overpressure adjusted to 2 and 5 bar using air flow rates in the range 8 to 100 m³/h according to the feasible measuring range of the air flow meter (type KSM-10105P20, Kobold Messtechnik, Germany). Air flow rates were kept constant during the measuring time. Videos were only used to estimate how well a closed bubble curtain as a two phase medium could be established.

6.2.1.2 Acoustic trials

Air pressure was set to 2 or 5 bar, air flow rate was adjusted at 10, 20, 30 and 40 m³/h. For practical reasons it was not feasible to use 40 m³/h with 2 bar pressure. Other parameters varied during the acoustic trials are summed in Table 6-1. Test signals were generated using a portable computer equipped with a National Instruments data acquisition board (NI DAQ PCI 6110, 1 MHz sampling rate) using DasyLab 7.0 (Measurement Computing, Germany). Emitted sounds were amplified by a Peavey IPA 300 power amplifier and transmitted through a Lubell Labs underwater speaker (LL 9162T). Received signals were acquired by two hydrophones (TC 4013 and TC 4014, Reson, DK), bandpass filtered and amplified (100 Hz highpass and 360 kHz low pass using ETEC B1501 amplifiers, filters are 2nd order, 12 dB/octave) and ultimately recorded with the same 6110 data acquisition board and the signal generation PC. In addition a Tectronix oscilloscope was used to monitor received signals (one inside and one outside the bubble curtain) in real time. The experimental configuration of the trials is depicted in Fig. 6-2.

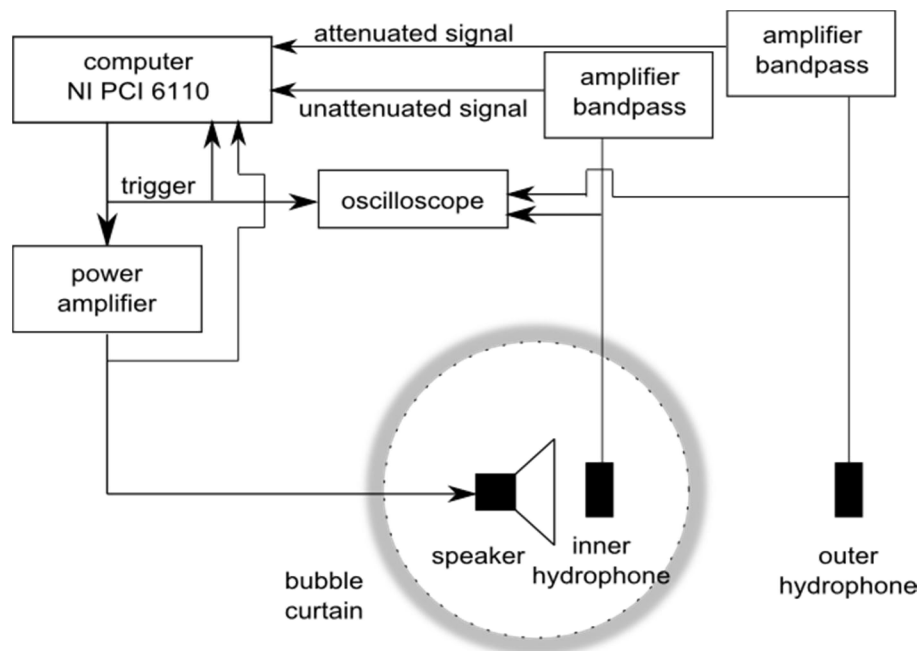


Fig. 6-2 Test of bubble curtain properties within a test tank. The Lubell LL 9162T speaker transmitted the signal within the bubble curtain. The signal was monitored using a fixed TC 4013 hydrophone located 0.19 m from the acoustic centre of the loudspeaker. The bubble curtain with a diameter of 0.68 m, resulting in 2.13 m active hose, was centred within the tank. The loudspeaker was centred within the curtain and TC 4014 outer hydrophone had a distance of 0.79 m to the loudspeaker. Tank size was 4.78 x 4.04 x 2.00 m, water depth was 1.74 m.

6.2.2 Trials in Kiel harbor

Trials in Kiel harbor were carried out using a 2.2 m radius circular full scale bubble curtain in the harbor basin. Acoustic measurements were performed much like the test tank trials, but with the addition of two autonomous recorders (PODs, Loughborough University, 96 kHz sampling rate, 24-Bit resolution) at 7 m and 30 m distance from the center of the bubble curtain (Fig. 6-3). A 16.9 m long pile of 0.5 m diameter was fixed to

the quay using metal bars of 5 m length. Unfortunately actual piling in Kiel harbor was not possible and hence test signals were produced by an underwater speaker placed close to the pile. Water depth was 9 m, and sediment consisted of muddy sea ooze of ~ 1 m depth followed by coarse sand and gravel.

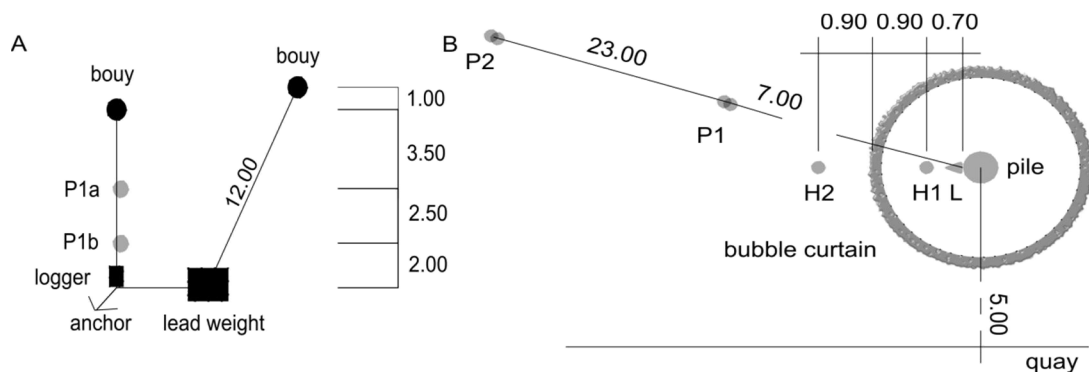


Fig. 6-3 Set up for test of bubble curtain in Kiel harbor A) mooring of hydrophones and noiselogger, B) sketch of positions of pile, loudspeaker (triangle – L), hydrophones H1 (TC 4014, Reson, DK) and H2 (HS 150, SRD, UK) as well as autonomous dataloggers with two hydrophones (P1 and P2, HS 70, SRD, UK), all distances in m, figures are not scaled. Numbers indicate distances between markers in m.

The bubble curtain itself was built as described in Fig. 6-4. It was fixed under a platform and lifted onto the pile in Kiel harbor using a 60 t crane. Afterwards the bubble curtain was lowered and unfolded in the water column until the base reached the sediment. This bubble curtain is supposed to be operated from a different ship than the one erecting the pile to save valuable time during the building process, or to be fixed under the pile frame to be easily lowered down after the pile is placed correctly. Individual layers are operated and controlled using stainless steel wires and can be adjusted to different water depth and current conditions. A modular approach is possible, however was not implemented during the trials, due to costs. Each nozzle pipe had a length of 2.5 m per side of the hexagon providing for 15 m active pipe per layer organized into three depth layers per module with 135 m overall active pipe length for all nine layers. Compressed air was provided by an oil-free screw-type compressor (Atlas Copco, P916, maximum air flow: 45 m³/min). Four dome-type pressure adjusting valves (GHR Hochdrucktechnik, Germany) were used to adjust the overpressure to the water depth of each of the modules of nozzle pipes independently to establish the same overpressure (3 bar) in all water depths. The lowest module was split into two compartments with the lowest ring having its own air supply to overcome sinking of the heavy foundation into the muddy sediment having an effect on bubble production. Maximum air flow rate per m nozzle hose was 0.33 m³/m min.

Measuring the air flow directly was not feasible, but an adjustment was possible using valves at marked positions, to realize 5 different uncalibrated air flow rates (termed descriptively as 0, 1, 2, 4, 8 where 0 is closed and 8 is opened completely). Tests before the acoustic trials showed that the compressor reached a maximum pressure of 10 bar, but was not able to deliver the full 45 m³/min at that pressure. However for shown results the pressure was limited to 3 bar adjusted to water depth and air flow rate was therefore kept constant (Fig. 6-5).

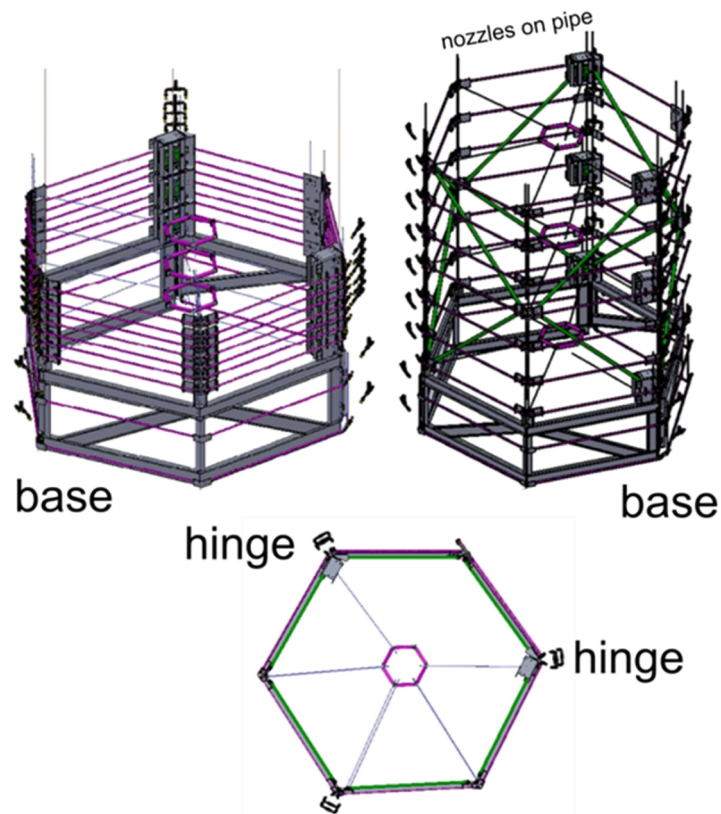


Fig. 6-4 Foldable bubble curtain used in Kiel harbor. The heavy base is lowered to the seabed using stainless steel wires and the bubble curtain unfolds during that procedure. Two elements of the hexagon can be opened so that the bubble curtain could be used independently of the piling ship speeding up the bubble curtain placement. Dimensions: inner radius: 2.2 m, fully unfolded height: 9 m. Hinges are operated using a seawater hydraulic system. Base was constructed from steel double T-sections, nozzle pipes were PVC-tubes of 32 mm diameter and 2.5 m length.



Fig. 6-5 Pressure adjusting valves, manometers and flow valves for adjusting air flow rate and overpressure.

6.2.3 Sound recordings and quantification

During the acoustic trials we used an underwater loudspeaker (LL9162T, Lubell Labs, USA) driven by a power amplifier (Peavey IPA 300) to emit narrow band sine wave pulses in a cosine envelope. Frequencies tested were 4, 8, 12, 16 and 20 kHz (test tank) and between 125 Hz and 20 kHz (trial in Kiel harbor). However results below 500 Hz and specifically at 3 kHz had to be removed due to insufficient amplitude. Pulses were repeated 50 times (test tank) and 25 times (field test) with 1 s repetition rate. Pulses had differing numbers of cycles to fix the duration (250 μ s during tank trials and 1 ms during field trials) of each pulse so that echoes did not interfere with the measurement of the received pulse. Thus, we measured only the direct path during all trials. The bandwidth of the transmitted signal was however larger in lower frequencies due to the lower number of cycles. Signal amplitudes (rms, peak positive and peak negative pressure) of amplified outgoing signal and the two hydrophones were measured using a custom written routine in DasyLab 7.0 (Measurement Computing, Germany). The program automatically triggered on the outgoing signal. SPL (rms) and L_{p-p} (peak-to-peak) as well as the waveform were saved to a file for later analysis in R 2.14.1 (R Development Core Team, 2012).

The speaker was driven at maximum output of the amplifier to reach maximum loudness during tests. Outgoing signals before and after amplification were monitored as well as the received signals on H1 and H2 (Fig. 6-3) and saved to file. SPL (rms sound pressure level) and L_{p-p}, (see Ainslie, 2011) were monitored and measured in real time. The sound exposure level of the pulse (SEL₉₀) was calculated to a 90 % energy criterion (see Madsen, 2005 for details) in an off-line process using a MATLAB routine according to this formula:

$$\text{SEL}_{90} = 10 \log_{10} \left(\frac{\int_{t_5}^{t_{95}} p^2(t) dt}{E_0} \right) \quad (\text{Eq. 6-1})$$

with E_0 being the references value of 1 $\mu\text{Pa}^2\text{s}$ and t_5 and t_{95} being the times when 5 % and 95 % of the energy of the pulse are reached. These metrics were chosen to match the dual criterion that has been proposed for German waters to protect harbor porpoises from hearing damage (SEL of 160 dB re $\mu\text{Pa}^2\text{s}$ and L_{p-p} of 190 dB re μPa in 750 m to ongoing pile-driving). Attenuation rates were then calculated as the difference in received level (SPL in test tank trials and L_{p-p}, SEL₉₀ in field trials) at the outer hydrophones without use of the bubble curtain (flow rate = 0) and the bubble curtain in operation.

6.3 Results

6.3.1 Tank trials

For field trials we decided on using spacings (s) of 7.5 cm using 1.5 mm nozzle diameter (d) because: Visual inspection of the small bubble curtain, Fig. 6-6, in the tank tests showed for s greater than 15 cm significant 'gaps', in the bubble stream. This could be seen unless both the nozzle diameter and/or flow rate were increased towards their upper limits. At closer spacing and higher flow rates these gaps became less evident with fairly uniform distribution of bubbles for 3.25 cm spaced nozzels for all nozzle

diameters (1 mm, 1.5 mm & 2.5 mm) tested for flow rates of 22 m³/h or higher. Different nozzle diameters did not obviously translate into different bubble diameters, however, different dispersal of bubbles in the water column was observed potentially due to the increases flow rates needed.

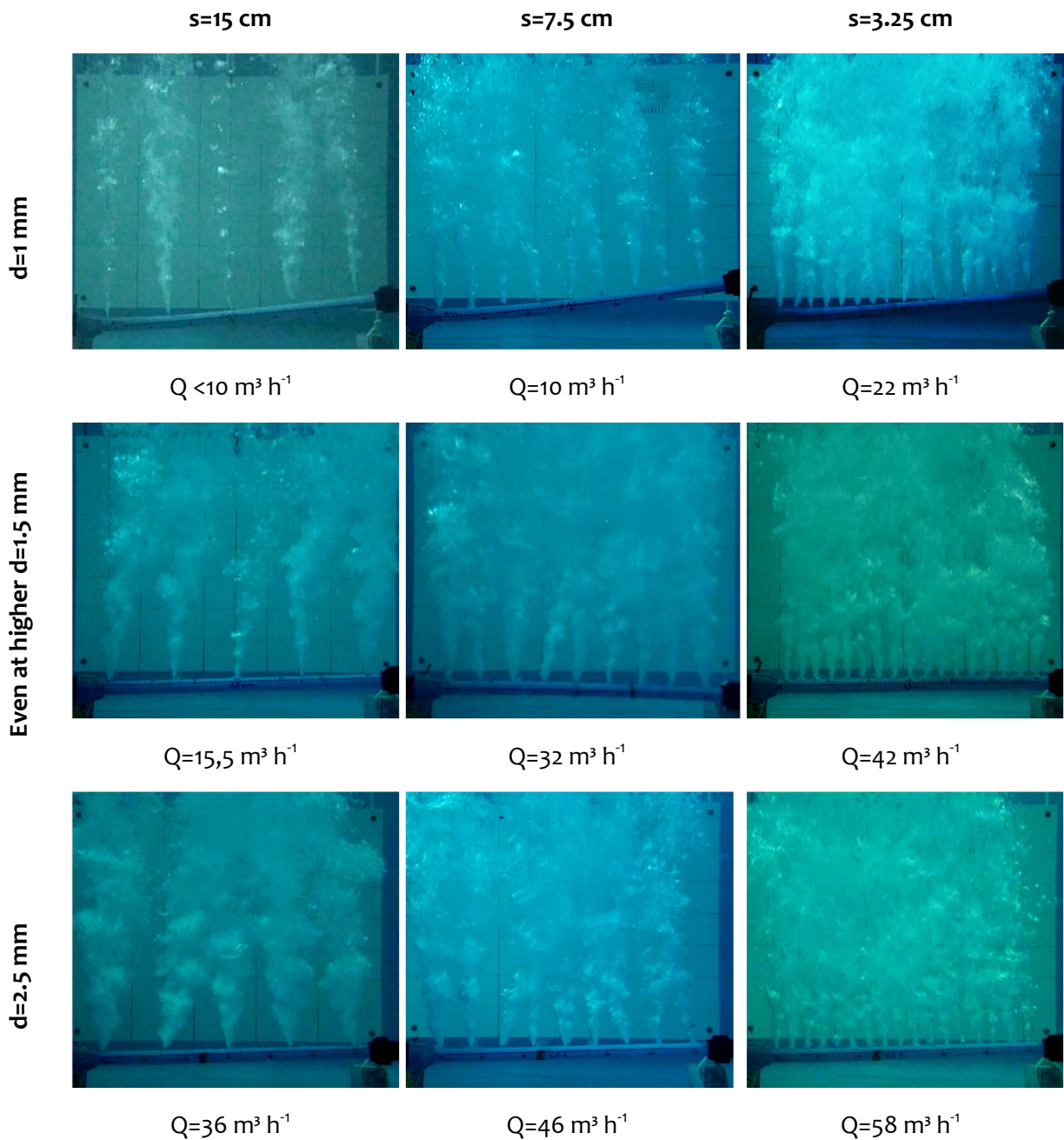


Fig. 6-6 Results of visual tests of the bubble screen at an excess air pressure of 5 bar. Different spacing (s) and nozzle diameter (d) lead to differently necessary air flow rate (Q) to form a closed (homogenous) bubble curtain.

It was decided to use 3 bar overpressure in Kiel harbor as acoustic tests of overpressure were inconclusive (not shown here) and higher pressures in the field experiment led to hysteresis effects in the compressor (varying pressure and air flow rate over time). Lowest level of the system for the field trial was set to alternating between 1 and 1.5 mm

nozel diameters at 3.25 cm spacing to allow development of a homogenous bubble curtain quickly above sea floor.

6.3.2 Acoustic Tank Trials

Results of the acoustic trials are summed in Fig. 6-7 and Fig. 6-8. With low air flow rates for all rings and for all pressures an approximately linear relationship can be observed – higher attenuations are observed for lower frequencies. Higher attenuation rates are also achieved with increased air flow rates, except for 4 kHz and 8 kHz, where the background noise created by the bubble curtain itself limits the usability of measurement data in the low frequency range. In these circumstances measurements comprised a mixture of bubble curtain self-noise and the test signal.

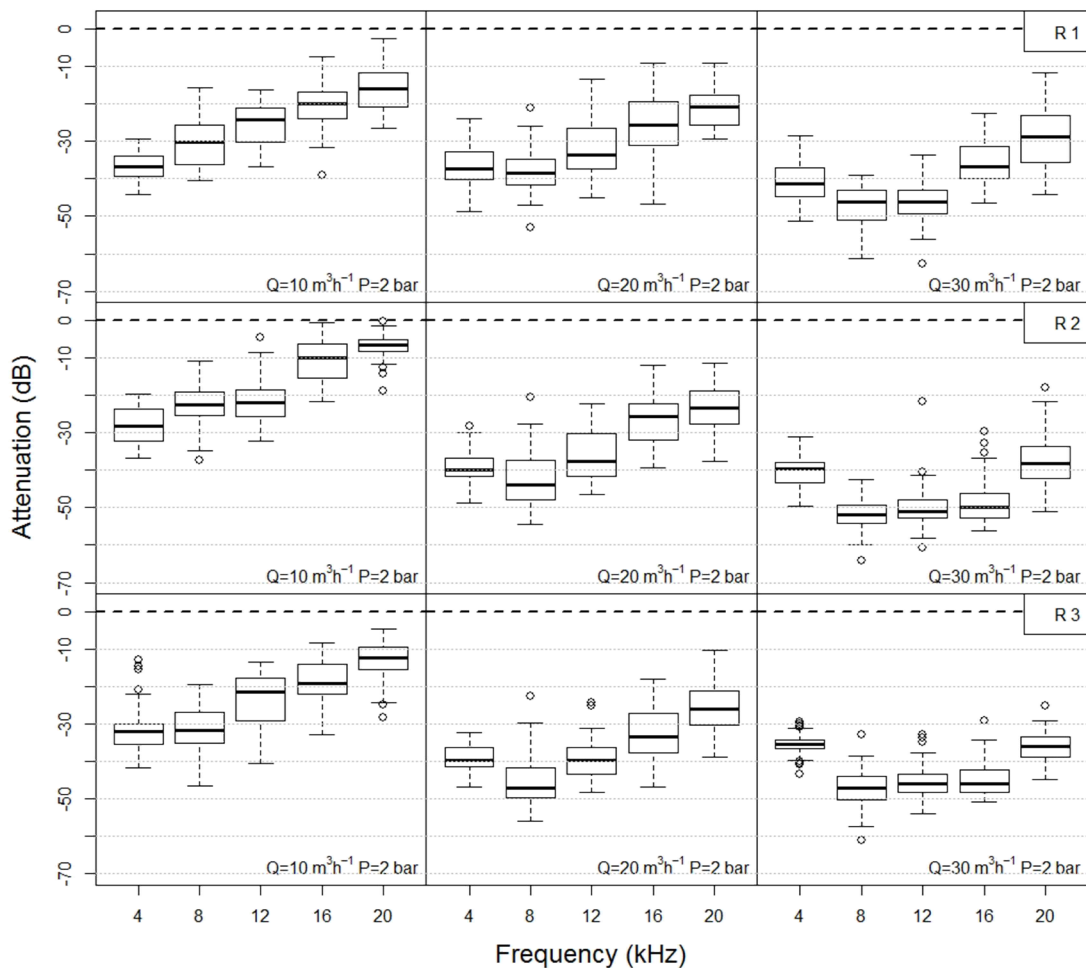


Fig. 6-7 Attenuation efficacy (SPL) for the sinusoid test signals for 2 bar overpressure. Results are given for the three tested rings (see Table 6-1) at varied air flow rate at five test frequencies. Boxes represent median, 25 and 75 percentiles and whiskers show 97.5 and 2.5 percentiles, circles show values outside the 95 % limits.

At relatively low air flow rates of 10 m³/h average attenuations of greater than 22 dB were achieved for the lowest test frequency of 4 kHz. Highest attenuation rates were found for R2 configuration at 8 kHz and a flow rate of 40 m³/h. Attenuation efficiency here was > 50 dB (Fig. 6-7, see Table 6-1 for details on rings). As stated before, those maximum results however may not represent accurate estimates of attenuation efficiency due to elevated levels of bubble curtain self-noise. Hence actual attenuation

could be higher. No consistent effect of overpressure (P) was observed. For R1 and R3 configurations lower pressures lead to a higher attenuation efficacy while for R2 higher pressures lead to a higher attenuation.

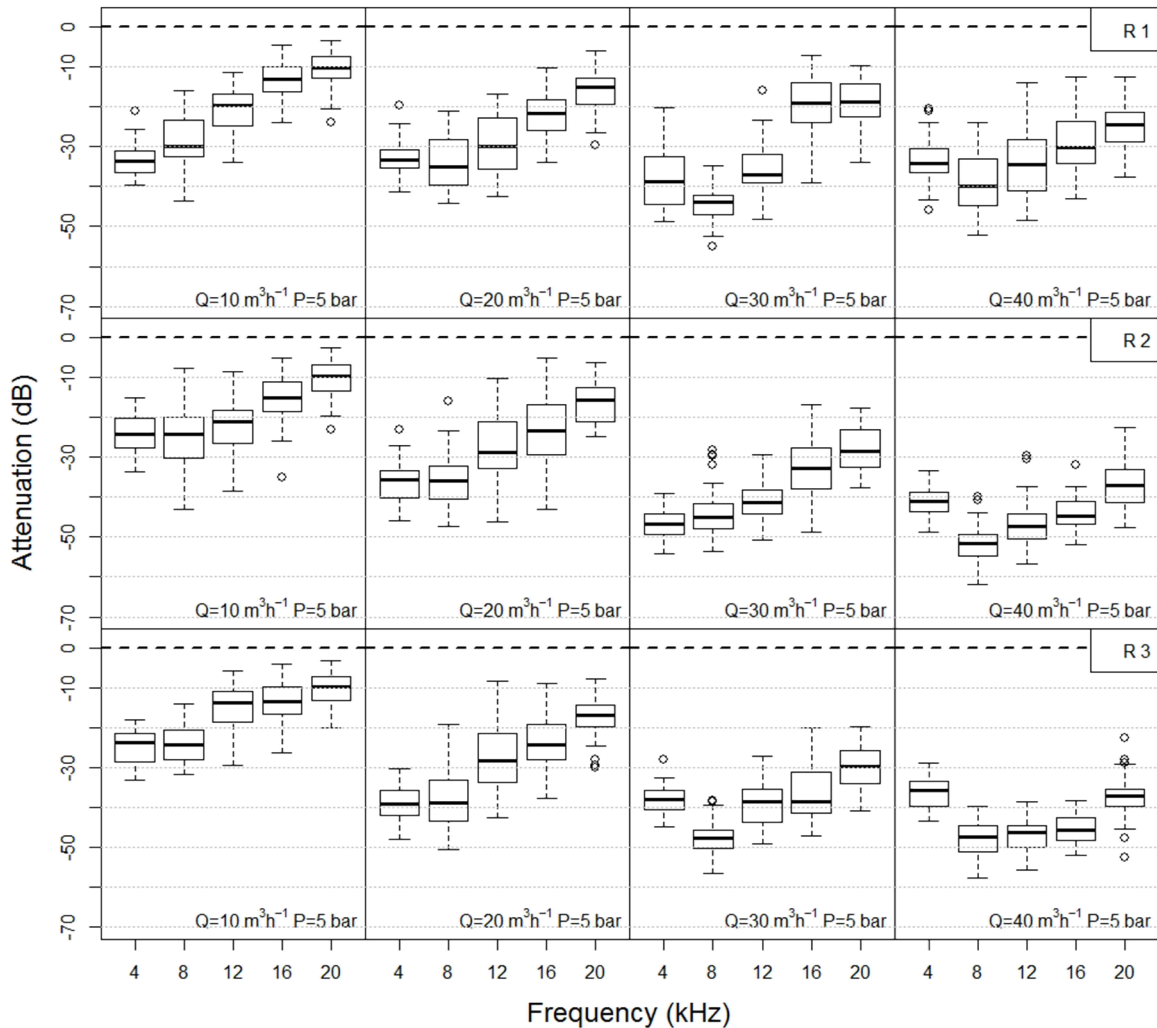


Fig. 6-8 Attenuation efficacy (SPL) for the sinusoid test signals for 5 bar overpressure at first nozzle. Results are given for the three tested rings (R1-R3, see Table 6-1) at varied air flow rate at five test frequencies.

6.3.3 Trial in Kiel harbor

All mechanical components worked fine for the trial situation. The bubble curtain self-noise and background/electronic noise during off situation (bubble curtain = 0) is presented in Fig. 6-9. Power spectral densities show that highest noise levels were found to be ≤ 500 Hz for air flow rates 1 and 2 and had a maximum at 1 kHz for air flow rates 4 and 8. Flow rates are verbal description of marked valve positions and hence represent different air flow rates, but cannot be directly transferred into quantitative air flow rates.

6.3.3.1 Attenuation efficiency

We will only describe the results of air flow rate 1 (barely opened valve) and air flow rate 2 (< 45 m³/min). Both of these air flow rates were below the efficiency curve of the compressor so ranged below 10 m³/min overall air flow rate translating into < 0.07

m³/min per running m pipe. Efficiency of air flow rates, greater than 2, could not be evaluated due to our inability to detect the test signal in the received waveforms. The inner hydrophone however clearly indicated that speaker and amplifiers were working normally. Amplitudes of the signal for air flow rates 0 - 2 were observed using an oscilloscope. Above flow rate 2 air bubbles drifted in between hydrophone and speaker and therefore could not be used to verify the outgoing signal.

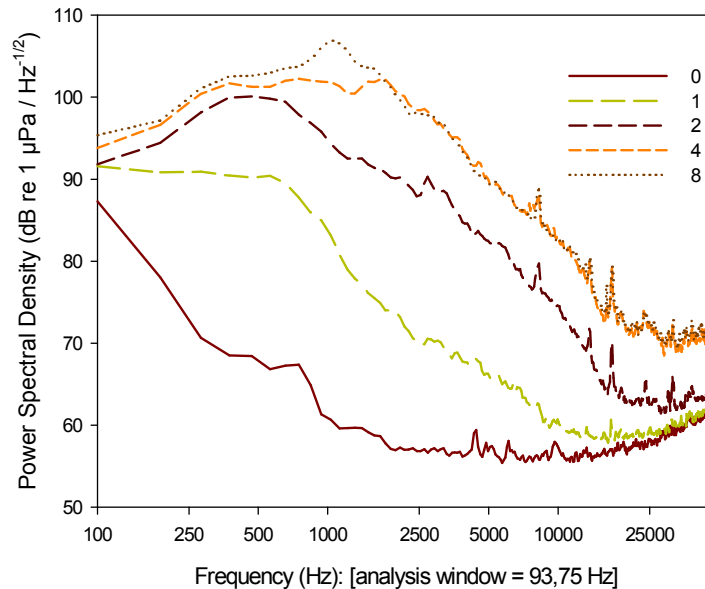


Fig. 6-9 Self-noise of the bubble curtain in 7 m distance from the center of the bubble curtain, 4.5 m water depth, 778 averages. State 0 includes background noise as well as electronic noise of the recording system with no air flow. Pressure was fixed at 3 bar and adjusted for four sections of the bubble curtain independently to match water depths.

Fig. 6-10 shows the attenuation efficiency of the tested signals for flow rates 0 and 1. Highest attenuation was found for frequencies above 8 kHz and is smallest at ~ 4 kHz. Below 4 kHz attenuation was found to be approximately constant ranging between 3.5 and 13.7 dB (mean: 8.4 dB) in Lp-p and from 2.2 to 11.2 dB (mean: 6.4 dB) in SEL₉₀. The mean attenuation rates recorded were higher for the station in 30 m distance (reduction in Lp-p of 9 dB and in SEL₉₀ of 6.9 dB) compared to 7 m (reduction of Lp-p of 7.8 dB and in SEL₉₀ of 6 dB). Lowest received levels were measured at 3 and 4 kHz and the speakers transmit response was not flat within the tested frequency range with a difference of 14.3 dB between maximum (179.3 dB re µPa L_{p-p}) and minimum (165 dB re µPa L_{p-p}) received level in 7 m distance.

When the bubble curtain was operated using air flow rates of more than flow rate 1, no signal could be detected within the bubble noise at the two positions in 7 and 30 m distance. However we can still calculate minimum attenuation rates by comparing the self-noise of the bubble curtain at flow rate 2 and the unattenuated signal when the bubble curtain was off in the power spectral densities (Fig. 6-11). This analysis highly depends on source level and hence frequencies with low source level, like 4 kHz, are measured to have less attenuation than other frequencies. The derived attenuation rates measured directly at the frequency of interest ranged between 15 dB at 4 kHz and 48.3 dB at 12 kHz with a mean attenuation of 36.5 dB (Table 6-2).

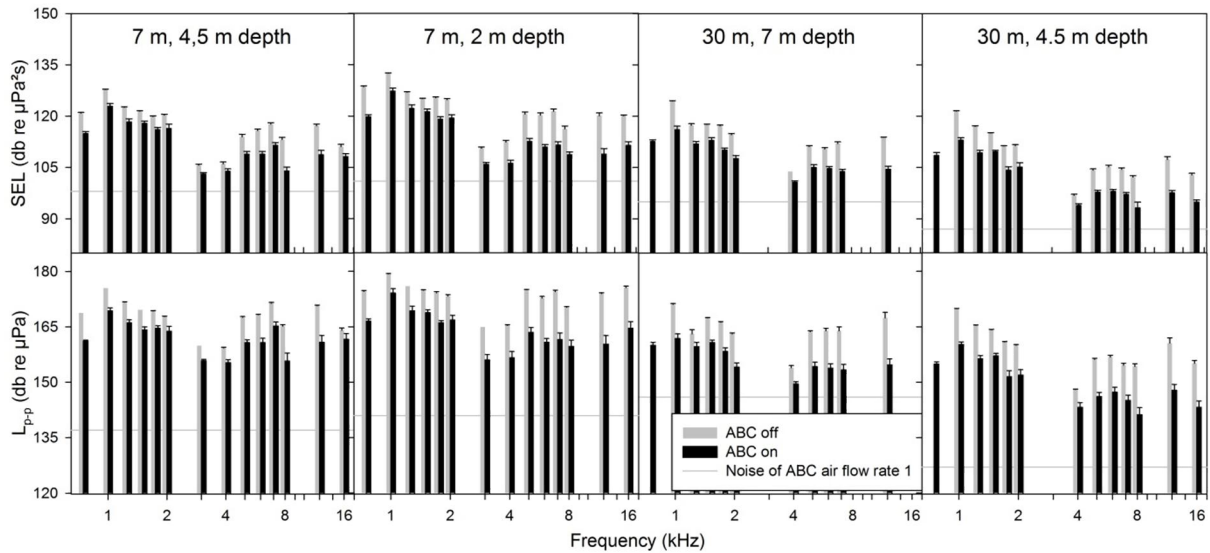


Fig. 6-10 Comparison of SEL_{90} and L_{p-p} for test signal during bubble curtain off (grey) and bubble curtain on at the lowest possible air flow rate (black). Grey line indicates the broadband self-noise of the bubble curtain at air flow rate 1.

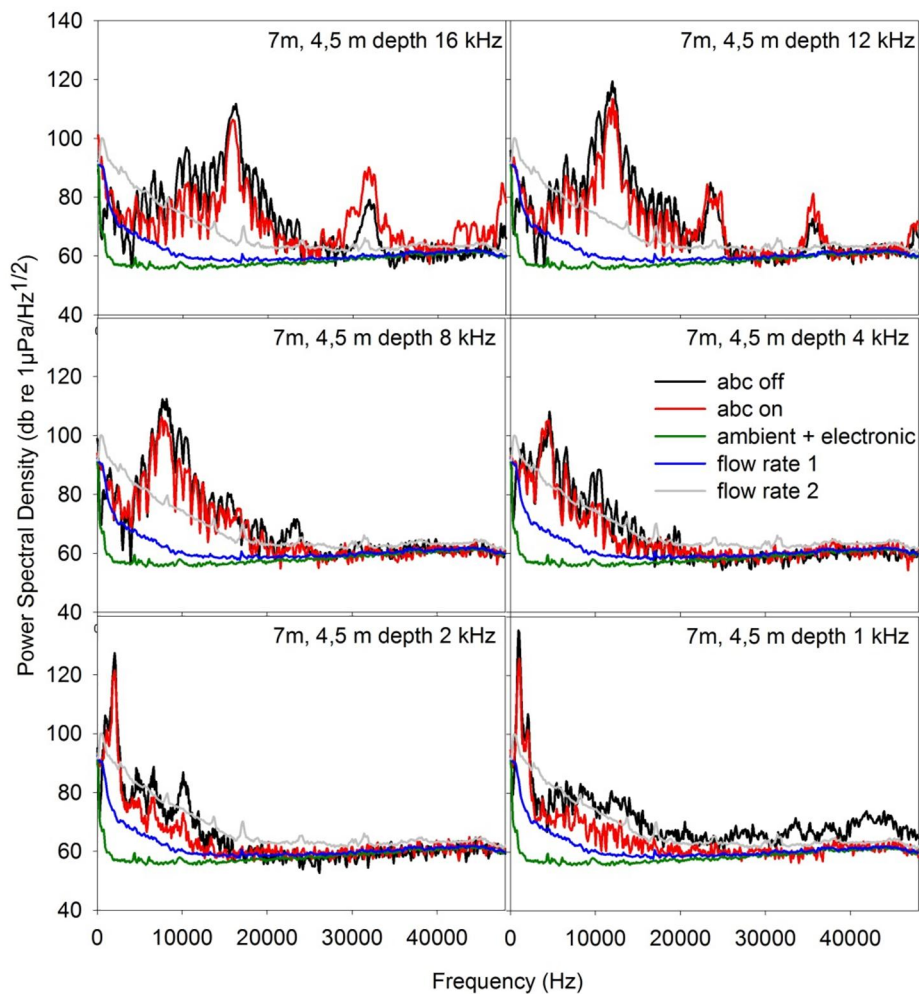


Fig. 6-11 Attenuation efficacy of the bubble curtain in Kiel harbor at the tested frequencies (black – bubble curtain off, red – bubble curtain on at lowest air flow rate 1) in comparison to the self-noise of the bubble curtain (blue – flow rate 1, grey flow rate 2) and ambient + electronic noise (green).

Table 6-2 Minimum attenuation efficiency of bubble curtain derived by comparison of the self-noise of the bubble curtain and the power spectral density of the unattenuated signal. Those values are to be understood as minimum values for attenuation efficacy. f = frequency.

f (Hz)	Selfnoise ABC at air flow rate α (dB re $\mu\text{Pa}/\text{Hz}^{1/2}$)	PSD of unattenuated signal (dB re $\mu\text{Pa}/\text{Hz}^{1/2}$)	Attenuation (dB)
20000	63.1	104.1	41.0
16000	64.4	110.8	46.4
12000	71.1	119.4	48.3
8000	77.9	108.8	30.9
4000	84.6	99.6	15.0
2000	90.1	124.7	34.6
1000	95.8	135.4	39.6

6.4 Discussion

6.4.1 Visual trials

Visual trials indicated that the production of a bubble curtain of singular separate circular bubbles at fixed spacing is not feasible in real world conditions for an unconfined bubble curtain. However, such an approach would have advantages due to interaction effects and can be realized using sponges and plastic air filled balls as described in Wilke et al. (2012). This would also lead to a better frequency control of attenuation. However, an unconfined bubble curtain has the advantage that it is easy to deploy and given that compressor output is sufficient produces reliable attenuation of sound in water with limited costs.

6.4.2 Acoustic trials

The tested bubble curtain systems showed very high efficiency in attenuating under water sound. Depending on frequency, the attenuation rate of the test system in Kiel showed at least 36.5 dB in mean attenuation compared to baseline. Tested frequencies ranged well above the frequencies of highest intensity for pile-driving sounds (ranging usually between 100 and 250 Hz) due to given geometries at the test site and capabilities of the underwater speaker used. However, hearing sensitivity for one of the species of concern, the harbor porpoise (Andersen, 1970; Kastelein et al., 2002) drops off sharply (approximately 35 dB) in sensitivity at frequencies of 1 to 0.25 kHz. For the harbor seals sensitivity also gradually decreases below 1 kHz, but not as steep (~15 dB between 1 and 0.25 kHz, Kastelein et al. 2009). For grey seals, the only available data on hearing abilities stem from cortical evoked potentials showing very high thresholds overall (Ridgway and Joyce, 1975). Recent results (Ruser et al., in press) show that similar to other seal species gray seals have best hearing capabilities above 4 kHz. Below 4 kHz high thresholds are found, most probably due to methodological issues of auditory evoked potential measurements. Attenuation rates of higher frequency content are thus likely of high importance, in order to avoid a behavioral reaction such as reported by Brandt et al.

(2011b), Carstensen et al. (2006), Dähne et al. (2013) and Tougaard et al. (2009) for porpoises.

The observed underwater sound attenuation levels were estimated using an underwater loud speaker generating pulses of sinusoidal signals. Thus these tests do not accurately reflect the impulsiveness of pile-driving or airgun sounds. However, it is very likely, that for these signals, sound attenuation will not decrease significantly. Another limitation of the tests using an underwater speaker is that only a very small proportion of the sound will be transmitted through the sediment. This transmission path is potentially very different for signals from a pile driving. In this case the pile is driven whilst in contact with three media: air, water and sediment. Sound is emitted in each of these media directly and the proportions vary with the fraction of the pile submerged in the water and the sediment penetration depth. Results of our study indicate that a high proportion of the noise – the fraction emitted into the water directly by the pile - can be attenuated using an ABC very efficiently. However, with a stacked bubble curtain close to the pile, emergent sound from the sediment travelling back into the water column will not be attenuated. When this energy exceeds the energy level of the directly transmitted pulse (through the water), then sediment transmission becomes the limiting factor of attenuation efficacy. These findings are in line with results of Reinhall and Dahl (2011a, b) who found that during pile driving a MACH wave is produced by a radial expansion of the pile propagating downwards at supersonic speed and thereby producing a MACH cone. Experiments conducted with a temporary noise attenuation pile (TNAP, a double walled steel tube) showed that the impulse directly transmitted into the water column was attenuated to virtual extinction, while the impulse transmitted via the sediment was not affected very much by the attenuation system situated close to the pile (Reinhall and Dahl, 2011 a, b).

The bubble curtain itself showed a tendency to create a flow in the test tank drawing the bubbles closer together on the water surface, than indicated by the diameter of the nozzle hose. This effect will be present in field trials as well, and has to be considered. Stacked bubble curtains will allow bubble emission in layers positioned throughout the water column which will counter act effects of tidal currents.

Although the bubble curtain for the test in Kiel harbour worked well it could still be considered as a scaled version of an at sea systems. For a useful at sea system the mechanical parts, however, must be better engineered and easier deployable.

6.5 Summary

The presented results confirm that an unconfined bubble curtains can achieve relatively high sound attenuation in the water column over the frequency range 1-4 kHz. From both the field, as well as the test tank trials attenuation rates of > 40 dB in SEL and Lp-p are possible. However, due to the fact that no actual piling was conducted during this study these documented attenuations are not directly transferable to an offshore pile-driving situation. Sediment conduction will alter the outcome, and may have strong effects depending on the substrate. Hence future studies should not exclusively concentrate on refining techniques for noise attenuation in water. Rather, research should also focus on the interaction between pile and substrate to find possible methods to attenuate sound conducted through a sediment path that can then emerge

back into the water column. This research is necessary in addition to mitigating the impacts of pile driving by using bubble curtains or other suitable measures for noise attenuation in the water column.

A further refinement in nozzle layout and setup may improve efficacy, but is most probably not needed, since the attenuation efficacy shown here exceeds expectations. Back propagated sound from the substrate may become more important as a noise source when effective waterbound noise mitigation measures (attenuation of ~ 10-20 dB) are used, than the directly transmitted impulse in the water column.

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6.7 Literature

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Synthesis

Acoustic methods for monitoring marine mammals have evolved considerably over the last decades due to major technological advancements in terms of data processing, storage capacity, as well as reliability of equipment. Additionally, energy requirements were reduced in such ways that now automatically operating devices like T-PODs, C-PODs, A-Tags, and PCLs are available for non-acousticians to carry out dedicated long-term field studies at reduced costs. While this has created a multitude of research opportunities, it also created problems in terms of data comparability between these new and previously used devices. New field methodologies need to be established to overcome these discrepancies. Major goals within this thesis were the establishment of calibration procedures for automatic echolocation click detectors for harbour porpoises, testing whether click detectors can be used for long-term monitoring in conservation efforts, analysing the impact of pile-driving during the construction of offshore wind farms, and testing of the efficacy of noise mitigation measures to reduce this potential impact.

1. Application of SAM for observing endangered populations

Can stationary acoustic monitoring (SAM) be used for the conservation of Baltic harbour porpoises? How can we use SAM for regular monitoring approaches, as well as in experimental setups most efficiently?

The long-term acoustic datasets described within chapters 1 and 3 can be seen as a starting point for monitoring of harbour porpoises in the German Baltic Sea. A clear geographical gradient with decreasing detection rates from west to east and seasonal changes from summer to winter that was previously only assumed was documented (chapter 1). These geographical and seasonal changes were used to design a study specifically aimed at analysing the habitat use of Baltic Proper harbour porpoises in German territorial waters (chapter 3). Thus, SAM has been shown to be a very helpful tool for monitoring the endangered Baltic harbour porpoise. The efficiency of acoustic monitoring to detect long-term trends has not been assessed during the study due to the fact, that longer study-periods (10 or more years of data) are necessary in order to detect meaningful trends. Within impact studies for offshore wind farms SAM and visual aerial surveys complement each other very well, when visual surveys are carried out on a large-scale to detect changes in distribution patterns. The data of echolocation click loggers, however, provides the necessary information on short-term displacement and temporal habitat use patterns.

A number of different studies have used SAM for research on endangered cetacean species (Jaramillo-Legorreta et al., 2012; Rayment et al., 2009, 2011; Sasaki-Yamamoto et al., 2013). The chapters presented within this thesis focussed on studying the seasonal and geographical differences within the Baltic Sea at very low detection rates and the differences caused by varying ecological factors and anthropogenic impacts. In principle SAM must not be restricted to endangered populations, but has shown high potential to be effective for analysing habitat use in specific areas when other, more traditional methods like dedicated visual surveys (e.g. Gilles et al., 2011; Hammond et al., 2013; Scheidat et al., 2008) or photo-identification (Würsig and Jefferson, 1990; Würsig and Würsig, 1977) fail. In the case of the Baltic harbour porpoise subpopulation, both of

these methods are not useful for obtaining abundance estimates or distribution patterns in the inner Baltic. Dedicated visual surveys fail because abundance is so low, that sightings on effort are sparse and robustness of estimates is not achievable (Berggren et al., 2002, 2004; Hiby and Lovell, 1996). Furthermore SAM has the advantage that it delivers data during day and night independent of light conditions. Photo-identification has only recently been started to be used on porpoises with some success in a confined area of the San Francisco Bay⁴, but search effort for the Baltic Proper would be much higher and the proportion of animals having identifiable ‘marks’ will be small.

The questions that can be answered by using SAM are manifold, and include estimating abundance, analysing habitat use, diel cycles, tidal dependencies and conducting impact monitoring as well as ecological modelling, all of which may have an important impact on conservation efforts, for endangered species or populations in particular.

Table 1 Detection ranges of automated click loggers for different species during stationary deployments. Although methodologies vary in terms of how the effective detection range was estimated, detection ranges for harbour porpoises are in the low hundred meters. For bottlenose dolphins estimated detection ranges are much larger. Furthermore for C-PODs the first results are just becoming available. For T-PODs the variations using instruments of varying sensitivity are large (Kyhn et al., 2012).

Source	Species	Effective detection range	Maximum detection distance	Frequency	Classifier/Difference	Device used
Rayment et al. (2009)	<i>Cephalorhynchus hectori</i>	198 m 239 m	431 m	130 kHz (A-Filter)	Cet all All Trains	T-POD
Kyhn et al. (2012)	<i>Phocoena phocoena</i>	17.10 - 42.18 m 24.13 - 49.93 m 47.39 - 107.84 m 34.54 - 84.82 m	-	130 kHz (A-Filter)	Cet all (15 s snapshot) All trains (15 s snapshot) Cet all (60 s snapshot) All trains (60 s snapshot)	T-POD V1, V3, V5
Philpott et al. (2007)	<i>Tursiops truncatus</i>	82 % of present groups detected in 500 m	1246 m	50 kHz (A-Filter)	Cet all + doubtful	T-POD V3
Bailey et al. (2010a)	<i>Tursiops truncatus</i> <i>Phocoena phocoena</i>	500 m -	~900 m -	50 kHz (A-Filter) 130 kHz (A-Filter)	Cet all	T-POD V4
Sasaki-Yamamoto et al. (2013)	<i>Platanista gangetica gangetica</i>	73.1 m (50 - 100 m, min-max)	< 100 m	65 kHz	-	A-TAG
Nuuttila et al. (2013)	<i>Tursiops truncatus</i>	211 - 497 m (feeding) 280 - 691 m (traveling)	1343 - 1779 m	30-150 kHz	High + Medium + Low classes (Kerno classifier)	C-POD

Although the detection ranges of the devices for high-frequency species, such as dolphins and porpoises, are small (Table 1), long-term data sets acquired with SAM data loggers will provide much insight into the echolocation behaviour of odontocetes, as well as into the ecological factors driving porpoise presence. In chapter 3 it was shown

⁴ http://www.ggcetacean.org/Harbor_Porpoise.html, accessed 16.11.2013

that these acoustic data sets can be used to analyse variations in habitat use. The distribution patterns found are most likely associated with freezing conditions in the Proper Baltic, as well as a preference for more saline waters, which was also found by Edrén et al. (2010) in an analysis of data from tagged porpoises of the larger Belt Sea area.

Methods for estimating abundance from static acoustic data loggers, or bottom mounted hydrophone arrays, have recently been presented for Blainvilles beaked whale *Mesoplodon densirostris* (Marques et al., 2009) using a form of cue counting by interpreting foraging clicks as the used cues. A cue production rate was estimated for that study using auxiliary data from an acoustic tag. A second approach using wider spread arrays and analysing whether cues are detected on multiple hydrophones in a spatially explicit capture-recapture approach was tested on minke whale *Balaenoptera acutorostrata* 'boing' sounds (Marques et al., 2010; Martin et al., 2013). These methods in adapted form have now also been applied to North Pacific right whales *Eubalaena japonica* (Marques et al., 2011), sperm whales *Physeter macrocephalus* (Ward et al., 2012), and fin whales *Balaenoptera physalus* (Harris et al., 2013).

For harbour porpoises the availability of auxiliary data becomes the most pressuring issue before an abundance estimate based on acoustic data can be achieved. These data are for instance cue production rates (e.g. average number of clicks per time interval detected on an acoustic tag deployed on a porpoise), average group size (through visual surveys in the area) and detection functions of individual detectors/deployments (through playbacks, visual monitoring or localization via hydrophone arrays). Although Kyhn et al. (2012) estimated abundance of porpoises based on a combination of visual and acoustic methods in a snapshot comparison, this method cannot be applied in the inner Baltic, as the used snapshot lengths of 15 and 60 s are much too short. Hence the resulting data set would have a tremendous overrepresentation of zeroes, also known as zero inflation. Nevertheless, the SAMBAH project (Static Acoustic Monitoring of the Baltic Harbour porpoise⁵) is focussing on this goal by employing 300 positions throughout the Baltic Proper in depths between 5 and 80 m (Gallus et al., 2011) in cooperation with the COSAMM project⁶. COSAMM is developing alternative methods for estimating detection ranges using playback experiments and hydrophone arrays.

Detection functions can be for instance calculated using hydrophone arrays around C-PODs to acquire the needed positions using a localisation based on the time of arrival differences (TOADs) on each hydrophone. The mismatch between the narrow echolocation beam of porpoises (Koblitz et al., 2012) and the necessary distances between the single hydrophones to achieve good localisation accuracy makes it necessary to develop new techniques for assessing the detection function of C-PODs out to at least 100 m. One possibility is using clusters of tetrahedral hydrophones. This can lead to a higher accuracy than the approach taken by Kyhn et al. (2012) estimating the detection function based on visual observations of animals at the water surface.

⁵ <http://www.sambah.org/> accessed 09.12.2013

⁶ <http://www.meeresmuseum.de/en/science/forschungsprojekte/cosamm.html>, accessed 15.11.2013

Although all of these methodologies are still under development, in the future they will provide researchers with possibilities to calculate abundance of harbour porpoises from SAM. Another possible step will be to use instruments like A-Tags with more than one hydrophone as for instance published by Sasaki-Yamamoto et al. (2013) analysing Ganges river dolphins *Platanista gangetica gangetica* diel patterns. Results indicated that it is feasible to differentiate group size and movement patterns by calculating the bearing towards the animals. This can be very beneficial, when the research aim is to analyse behavioural patterns, like for instance during pile-driving, when the speed of porpoises could be an indication of whether the animals speed up during noise emission to evade the direct surroundings of the wind farm. A similar approach was used to observe differences in tidal habitat use of Indo-Pacific humpback dolphins *Sousa chinensis* finding that riverine stations recorded less dolphin activity during ebb tide, while offshore stations did not show such dependencies (Lin et al., 2013).

Within this thesis diel cycles in porpoise echolocation behaviour were found in the North Sea (chapter 5), although their influence was smaller than the seasonal variation in the acoustic registration rates. For the Baltic Sea no diel pattern was detected (chapter 3). Other data on diel cycles in harbour porpoise activity exist from tagged animals. Linnenschmidt et al. (2012c) conducted tagging studies on three free ranging harbour porpoises and found a strong indication of diel behaviour with high echolocation rates during the night in concurrence with elevated diving activity. One of the animals, the only female, did not show a pronounced diel cycle, highlighting, that due to very small sample sizes acoustic tag data have to be treated with care. In chapter 3 and 5 diel cycles were also investigated and had a highly variable influence on detection rates – there was no detectable diel pattern in the Baltic Sea data set and only low influences for the area around the wind farm *alpha ventus*. Diel cycles were also analysed by Carlström (2005), who used a limited data set of T-POD recordings (2 month duration) from Scotland showing increased echolocation activity at night. Similar results were found at the Dogger Bank around offshore installations (Todd et al., 2009). Porpoises were recorded on T-PODs more often at night and used shorter click intervals below 10 ms indicating nighttime feeding activity (Koschinski et al., 2008). This behaviour can also be seen in the Baltic Sea (Schaffeld, 2011). Four positions in the Wadden Sea, however, did not show a very pronounced diel cycle, but were strongly influenced by tidal changes (Dähne et al., 2012) and one station in the Sylt Outer Reef showed a highly significant diurnal cycle with more detections during the day than during the night (Ludwig et al. unpublished data) possibly in relation to a vertical migration of sand eels (Jensen et al., 2003). These differences highlight that the habitat use of porpoises is highly diverse and depends strongly on the available prey species and their variable distribution patterns throughout the day reflecting for example vertical migrations. Based on 6 week C-POD deployment periods around the Great Belt Bridge in Denmark on 16 - 27 positions Brand et al. (2014) hypothesized, that besides circadian cycles, water depth may play a role in diurnal registration rates due to the different available prey items.

Another factor, which has not been studied sufficiently yet, may be that porpoises presumably use echolocation less frequently during unihemispherical sleep which may occur in 5 – 10 % of their time (Wright et al., 2013b) effecting detection probabilities of SAM.

2. Implications of calibration results for SAM-studies

What are the acoustic properties of currently employed instruments used for SAM and how do these properties influence results of environmental impact assessments as well as long-term monitoring?

Within this thesis the detailed knowledge about the instruments (T-PODs), as determined by conducting a rigorous calibration (chapter 2), helped to set up a framework for conducting experiments using comparable methods and instruments. For C-PODs the calibration procedure had to be adjusted to the larger frequency range and the modified detection algorithm compared to T-PODs, in order to describe differences between the instrument types (chapter 4). It is crucial to use such knowledge in field experiments like analysing displacement patterns of porpoises with regard to offshore wind farms (chapter 5), since differences in instrument sensitivity may lead to biased conclusions about displacement ranges and the duration of these effects.

The results of chapters 2 and 4 showed that variations in T- and C-POD detection thresholds exist and are not per se negligible. Any variation in detection thresholds will alter the volume of water that is being observed and hence the probability that porpoises are registered in the vicinity of the POD. Some theoretical considerations highlight why field trials of deploying PODs close together in packets will have great difficulties to analyse how instruments compare in a field situation.

Firstly, the volume of water observed depends on water depth and deployment depth of the instrument. Since the detection radius of T-PODs is in the order of 20 to the low hundred meters (Table 1) the volume (see Verfuß et al. (2010)) can be either

- a sphere (deployment in the middle of the water, detection radius < half of water depth),
- a half sphere (deployment on surface or on bottom, detection radius < water depth), or
- a segment of a sphere (detection radius > minimum distance to surface or bottom).

These relations become even more complicated when we consider that the detection radius (or effective detection radius, see Kyhn et al. 2012) is only a description of where the same number of animals/clicks/trains are missed inside the volume as are recorded outside the volume. Hence the simple relation between deployment depth and water depth has a large influence on results by altering the detection function. The same would be true if the animals spend more time at the surface than at depth. This would also have implications for visual surveys for correcting for animals missed on the transect line: the percentage of time spent within the upper 2 m was reported to be 55 % (45 – 63 %) for 14 satellite linked dive recorders deployed on porpoises in the Danish Belt Sea (Teilmann et al., 2007) and ranged between 28 and 54 % for six porpoises in Danish waters (Wright et al., 2013a). Furthermore the presence of a pycnocline can alter the detection function. All of the above mentioned factors may vary between the area and time of POD deployment in a package (for direct comparison measurements) and hence very long deployment periods in different areas would be necessary to derive a more generalized function of sensitivity within these trials.

These theoretical considerations imply that a calibration in a test tank is the preferred method to measure differences in detection thresholds between devices. This becomes even more important, when it is considered that other settings used during the study may alter the detection thresholds. The best practice method is to use a predefined detection threshold (T-PODs) and adjust all instruments via the sensitivity/minimum intensity setting to this level. This is not feasible for the C-POD which has no setting for adjusting the sensitivity. Devices that have pronounced horizontal variations should not be used in field trials, as the mean device sensitivity may not be the appropriate value to characterise the detection area. However, most of the devices tested at 130 kHz performed in a narrow range (chapter 4), indicating that the effective detection ranges will be comparable. First results of studies estimating detection ranges for C-PODs show a large variation in effective detection radius for bottlenose dolphins ranging from 211 to 497 m during feeding and 280 to 691 m during traveling (Nuuttila et al., 2013, for comparison see Table 1). The frequency range that bottlenose dolphins use in contrast to harbour porpoises is much larger (30 - 150 kHz) and therefore a tight standardisation at 130 kHz does not indicate comparability for bottlenose dolphin echolocation clicks. These findings are very much in line with our calibration results, showing higher variation in the lower frequency band below 100 kHz.

In conclusion future studies should incorporate:

- A calibration of instruments under controlled conditions, especially when species using the lower frequency range (20-100 kHz) are to be monitored.
- A thorough analysis of how differences in sensitivity can affect the results taking water depth and deployment depth into account.
- A standardised method of deployment to keep recording conditions and hence observed volumes of water as comparable as possible.⁷

Furthermore, the instrument settings that were used during the study should be clearly stated.

3. Cumulative impacts and their implications for future research

What are the influences of the construction of an offshore wind farm on porpoises?

Porpoises in the German North and Baltic Seas are subject to varying anthropogenic threats. In the past, dedicated hunting in the Baltic Sea was presumably the largest factor with around or above 1,000 animals taken in the Danish drive fishery prior to the 20th century (Kinze, 1995). In the 20th century incidental by-catch in fisheries (e.g. Kock and Benke, 1996), prey depletion due to overfishing and habitat destruction (DeMaster et al., 2001), pollution (e.g. Beineke et al., 2005; Das et al., 2006a, 2006b; Siebert et al., 1999) and potentially noise pollution (OSPAR, 2009; Wright et al., 2007) may have increased stress to harbour porpoises. Additionally contaminants such as PCB (polychlorinated biphenyls) and PBDE (polybrominated diphenyls), amongst others, can lead to a suppression of the immune system (Beineke et al., 2005, 2007) and dysfunction of the thyroid gland (Das et al., 2006b). Nowadays incidental by-catch in fisheries is still

⁷ In our studies we used deployments preferably in medial water depth (Baltic Sea: 5-7 m below surface for water depth up to 28 m, North Sea: 10 m above sea floor for water depth between 25 and 35 m).

thought to be one of the major reasons why porpoises in the Baltic Proper do not recover (e.g. Berggren et al., 2002; Gallus et al., 2012).

However, a major source of disturbance with potentially detrimental effects are new plans to build offshore wind farms using percussive pile-driving in large regions of the North Sea and, to a lesser degree, in the Baltic Sea. Although first results indicate, that porpoises may use offshore wind farms in the North Sea as sheltered areas with likely higher food availability due to an artificial reef effect (Scheidat et al., 2011), in the Baltic Sea the negative effects of the construction period took 10 years to disappear (Teilmann and Carstensen, 2012). Hence all available results at the moment (Bailey et al., 2010b; Brandt et al., 2011; Carstensen et al., 2006; Tougaard et al., 2009a) are still first case studies in different areas with effects differing from site to site. For example the study described in chapter 5 (Dähne et al., 2013) was carried out in an area where (at the time of the study) porpoises naturally occurred in low densities compared to the two hot spot areas in German waters at the Sylt Outer Reef and the Borkum Reefground. In high densities areas the results could differ since in regions where porpoises accumulate either prey availability will be high, or the area is used for social interaction like mating, calving and nursing. Porpoises may then actually endure the acoustic impact over prolonged times and can thus be subject to an increase in stress levels. Müller et al. (2013) proposed to measure stress hormones and mRNA-expression of cytokines and acute-phase proteins to quantify these possible effects. Furthermore, due to a prolonged exposure to loud anthropogenic noise the behaviour of cetacean species may be altered. Kastelein et al. (2013a) found that a harbour porpoise exposed to playbacks of pile-driving noise showed an increased respiration rate at a sound exposure level (SEL) of 133 dB re $\mu\text{Pa}^2\text{s}$. At even higher levels the porpoise also jumped out of the water, a behaviour that porpoises rarely show in the wild. These findings compare well to the results of chapter 5, where a displacement of porpoises was found above an SEL of 139 dB re $\mu\text{Pa}^2\text{s}$ in real pile driving conditions. One of the main conclusions from that study was that porpoises do need time to move away from the piling source and it remained unclear from the study results, whether porpoises had already stopped to move away further when pile-driving was finished. Additionally, an increased respiration rate as a sign of physiological stress does not necessarily imply a behavioural flight response.

For the North Sea it is currently planned to generate 25 GW electricity in 2030 (BMW, 2012). This will result in approximately 5,000 turbines overall and hence (because some foundations will have multiple piles) approximately 10,000 piles to be installed over a period of 17 years resulting in approximately 500 piles per year. Weather conditions are not always suitable for offshore construction work. When we assume that 200 working days are available per year, 2.5 piles have to be installed each day to reach the proposed goal. Hence reactions of harbour porpoises being scarred between several construction sites are very likely and will increase general stress levels, energy expenditure, decrease time available for feeding and may ultimately have an effect on reproductive success. Cumulative effects of several wind farms being built during the next decades will therefore have a potentially more severe impact, than those recorded today at single sites.

But cumulative impacts would also include all other natural and anthropogenic stressors. If we assume that there is an effect of climate change on porpoises, as has been

proposed for colder waters (Heide-Jørgensen et al., 2011; MacLeod et al., 2007), then we would find a general long-term trend that cannot be attributed solely to wind farm developments. Therefore, research must include all anthropogenic and natural cumulative effects to make an estimate of the likely impact of single stressors.

4. Mitigation strategies

How can acoustic methods for noise mitigation be applied to effectively protect harbour porpoises from potentially harmful impulsive sounds?

Mitigation devices to attenuate underwater sound emissions (chapter 6) will hopefully reduce the impact of pile-driving on porpoises. The air bubble curtain, as one possible easy to use system was investigated within this thesis. The bubble curtain tested here performed better than any previously reported noise mitigation system (Lucke et al., 2011; Reinhall and Dahl, 2011; Wilke et al., 2012; Würsig et al., 2000). However, it must be stressed, that these results cannot be directly transferred to real pile-driving conditions, when the sound source is a line source (not a loudspeaker, as in our study) that, next to emitting sound into the water column, is connected to air and the sediment. This situation would lead to different paths of sound propagation, especially into the sediment. The back-propagated sound from sediment into the ocean in some distance from the pile will limit the mitigation efficiency of any used mitigation screen that is working only in the water column close to the pile.

The German nature conservation and maritime agencies currently propose that noise emission into the ocean should be limited to an SEL of 160 dB re $\mu\text{Pa}^2\text{s}$ and L_p of 190 dB re μPa in 750 m distance to the source. This value would prevent hearing damage in the form of TTS for a single strike as measured on one porpoise in captivity (Lucke et al., 2009). However, when sound emissions are limited to being as low as feasible, the possibility for a behavioural reaction is reduced as well. This has been demonstrated for the first offshore wind farm, the Trianel Windpark Borkum, that was installed using noise mitigation measures throughout the construction period. The displacement radius and hence the number of affected individuals was drastically reduced (Diederichs et al., 2013; Pehlke et al., 2013).

These trials in the open sea north of Borkum and trials on a pre-piled test pile in the Kiel Bight (Germany, Wilke et al., 2012) resulted in the conclusion, that when evaluating the efficiency of noise mitigation systems, the changed frequency content has to be considered as well. In the trials presented in this thesis these findings were incorporated by testing single frequencies. Porpoises use only a narrow band around 130 kHz for their echolocation signals (Au, 1993). Their hearing thresholds in the lower frequencies (<10 kHz) are high compared to their best hearing sensitivities between 16 and 140 kHz (Andersen, 1970; Kastelein et al., 2002, 2010; Lucke, 2008). Pile-driving sounds in contrast have their highest energy around 200 - 300 Hz (Betke and Matuschek, 2011; Brandt et al., 2011), but extend into the higher frequency range. An SEL of 160 dB re $\mu\text{Pa}^2\text{s}$ is a broad band measure of sound energy and currently efforts are concentrated on attenuating the frequencies of highest energy to stay below the set limit (for preventing direct hearing damage for porpoises). But when this first step is accomplished, the next challenge will be to quantify which band is causing the displacement of porpoises in terms of a behavioural reaction. It is likely that those are higher frequencies, which are

generally better perceived by porpoises. In addition similar studies should also be conducted for seals. Although first results from the UK indicate that documented effects on harbour seal and grey seal haul out counts close to the Scroby Sands wind farm could not be directly linked to the wind farm construction period (Skeate et al., 2012), more data is needed to evaluate the effects of offshore construction on these species.

5. Outlook and further research needs

Within this thesis the applicability of SAM was tested for monitoring porpoises in the German Baltic Sea and for small-scale impact studies focussing on wind farm construction. Further research is needed for large-scale applications like abundance estimates of harbour porpoise for the entire Baltic Sea (SAMBAH⁸), but also to use SAM for cumulative impact assessment of multiple wind farms being constructed simultaneously and successively over the next decades. These cumulative impact assessments must also consider other anthropogenic and natural stressors for predicting the effects of individual wind farms in the ecological context of the North and Baltic Seas. Overall, the different anthropogenic impacts need to be balanced at a level which secures a good environmental status for harbour porpoise in the North and Baltic Seas. Calibration of monitoring instruments will be a vital tool to provide means of making data comparable across borders and will allow comparability of instruments over long time periods when a successive progress of the instrument capabilities will lead to better detection rates or larger effective detection ranges.

The use of stationary acoustic monitoring (SAM) for harbour porpoises (*Phocoena phocoena*) has shown to be the only method currently applicable to analyse the fine-scale temporal habitat use of porpoises. In particular it has major advantages over traditional line transect surveys in low density areas like the Baltic Proper. Conservation of harbour porpoises, a species with wide spread distribution and seemingly very large variation in habitat use, which is related to varying prey availability in a changing environment, calls for even larger scale studies than conducted within this thesis and irrespective of country borders. Within long-term studies, such as national monitoring programs (e.g. Gilles et al., 2012) or large European survey campaigns, such as SCANS, SCANS II and a future SCANS III, SAM with a high temporal resolution, but limited spatial capabilities, can serve as one means to analyse, when specific changes in habitat use are happening and subsequently finding the cause for this change.

For noise mitigation in the context of offshore windfarm construction, future studies should focus on developing 'quiet foundations', i.e. foundations that do not require impulsive pile-driving or other noisy procedures. This research should be prioritized over developing means of noise mitigation for pile-driving. Quiet installation techniques lead to a generally reduced noise emission, which all other marine mammals as well as fishes will likely benefit from.

⁸ <http://www.sambah.org/> accessed 09.12.2013

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Description of the individual scientific contribution to the multi-author papers

Chapter 1

Geographical and seasonal variation of harbour porpoise (*Phocoena phocoena*) presence in the German Baltic Sea revealed by passive acoustic monitoring

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Individual contributions: UKV, CGH, and HB developed the idea and design of the study. CGH and MD conducted most of the field work together with staff of the harbour porpoise research team of the German Oceanographic Museum, UKV, RM, AM, MD, and CGH analysed the data. MD programmed the data base that the authors used for data analysis. Graphic representations of GIS analysis were done by MD. UKV and all authors discussed the results and UKV wrote the manuscript which was reviewed by all co-authors.

Chapter 2

Determining the detection thresholds for harbor porpoise clicks of autonomous data loggers, the Timing Porpoise Detectors

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Individual contributions: UKV developed the idea for the study. Discussions of UKV and MD influenced the design of the carried out experiments. MD programmed a data base for data analysis. MD, MJ, AGa and UKV carried out most of the experiments conducted. HB provided facilities for conduction of experiments. UKV, MD and MJ analysed and evaluated the data. UKV wrote the manuscript and it was reviewed by all co-authors.

Chapter 3

Use of static passive acoustic monitoring to assess the status of the ‘Critically Endangered’ Baltic harbour porpoise in German waters

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Individual contributions: AGa, UKV, HB and MD designed the study. MD and staff of the harbour porpoise research team of the German Oceanographic Museum carried out the

field work. MD, AGa, UKV and SA analysed and evaluated the data. SB and US provided necessary input for protective legislation and status of harbour porpoises in the Baltic Sea. MD and AGa wrote the manuscript and all co-authors reviewed and accepted it before submission.

Chapter 4

Methodology and results of calibration of tonal click detectors for small odontocetes (C-PODs)

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Chapter 5

Effects of pile-driving on harbour porpoises (*Phocoena phocoena*) at the first offshore wind farm in Germany

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Individual contributions: AGi, KL, US and MD designed the study. MD, KL and JS carried out the field work for the static acoustic monitoring, VP and AGi carried out the aerial surveys. MD, SA, VP, AGi and JS analysed and evaluated the data and results. KK calibrated the C-PODs in Stralsund. MD, AG and VP wrote the manuscript and all co-authors read and approved the manuscript before submission.

Chapter 6

Testing the efficacy of air bubble curtain for noise mitigation in offshore construction work

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Individual contributions: MD, KL and US designed the study. MD, AR and KL conducted the experiments. PAL provided necessary software for data evaluation and equipment

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Curriculum vitae

Personal data

Name	Michael Dähne
Birthdate	05/06/1975
Birthplace	Potsdam-Babelsberg
Nationality	German

Education

1981-1983	Carl-von-Ossietzky Schule, Werder (Havel)
1983-1990	POS 47, Adolf Hausmann, Potsdam
1990-1995	Weinberggymnasium Kleinmachnow, Brandenburg, school is specialised in mathematics and natural sciences Graduation: A-Levels (Abitur)
1998-2005	University Rostock Graduation: Diplom-Ingenieur (equivalent to master of engineering) for land management and environmental protection
2004-2005	Diploma thesis "Development and calibration of a numerical groundwater model for the water catchment Kühlung (Bad Doberan)"
From 2009	Dissertation at the Christian-Albrechts-University Kiel

Work experience

1995-1996	Alternative civilian service at the rescue center of the 'Ernst von Bergmann' hospital Potsdam
1996	Work for an electrician and construction firm
1996-1997	Internship at 'Firma Biberschwanz', reconstruction of timbered houses and re-use of recovered materials
1997-1998	Au-pair year in the USA, Pittstown, NJ
2004-2006	German Oceanographic Museum: Research assistant within multiple projects on passive acoustic monitoring of odontocetes
2005-2006	Freelance work: Database engineering for marine mammal monitoring (strandings database, T-POD database), designing of user-interfaces for databases to assure data safety and practicability
2006-2009	German Oceanographic Museum: Scientist in research and consulting projects on monitoring harbour porpoises and using new technologies

2009-2011	(aerial photography) for monitoring/assessment. Research and Technology Centre of the Christian-Albrechts-University Kiel: Scientific work on the use of bubble curtains for noise mitigation during pile-driving.
2011-present	Scientist in research projects covering effects of noise on marine mammals, analysis of habitat use, ecological modelling, using auditory evoked potentials on harbour porpoises and seals to determine hearing thresholds and sensitivity to noise.

Workshop and conference organisation

2008	Organizer of the Workshop “Remote sensing to assess the distribution and abundance of seabirds and marine mammals: Possible future applications for Unmanned Aerial Vehicles (UAVs)” held in Stralsund 20-21 November 2008 (Co-organizer: Dr. Görres Grenzdörffer, University Rostock)
2009	Co-organizer with Robin Angliss (NOAA, USA) of the workshop: “Using unmanned aircraft systems to study marine mammals and other wildlife species” at the Biennial Conference of the Society for Marine Mammalogy 2009, Quebec, Canada
2010	Technical organizer of the 24 th Annual Conference of the European Cetacean Society in Stralsund, Germany, organizer of the video night, member of the scientific committee

International bodies

2013	ICES – International Council for the Exploration of the Sea, Member of the Working Group on Marine Mammal Ecology (WGMME)
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Memberships

since 1995	NABU and WWF
since 2005	European Cetacean Society
since 2007	Society for Marine Mammalogy
since 2011	Acoustical Society of America

Reviewer

Journal of the Marine Biological Association of the U.K.

Publications

Peer reviewed

- Ruser, A., Dähne, M., Sundermeyer, J., Lucke, K., Houser, D., Finneran, J., Driver, J., Pawliczka, I., Rosenberger, T., and Siebert, U. (in press). "In-air evoked potential audiometry of grey seals (*Halichoerus grypus*) from the North and Baltic Seas," PLOS one.
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- Dähne, M., Gilles, A., Lucke, K., Peschko, V., Adler, S., Krügel, K., Sundermeyer, J., and Siebert, U. (2013). "Effects of pile-driving on harbour porpoises (*Phocoena phocoena*) at the first offshore wind farm in Germany," *Environ. Res. Lett.*, **8**, 025002.
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- Dähne, M., Peschko, V., Gilles, A., Lucke, K., Adler, S., Ronnenberg, K., and Siebert, U. (in press). "Marine mammals and windfarms: Effects of alpha ventus on porpoises," In BSH & BMU (Eds.), "Ecological research at the offshore windfarm alpha ventus - Challenges, results and perspectives" Federal Maritime and Hydrographic Agency (BSH), Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), (Springer Spektrum).
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- Liebschner, A., Seibel, H., Teilmann, J., Wittekind, D., Parmentier, E., Dähne, M., Dietz, R., Driver, J., van Elk, C., Everaart, E., Findeisen, H., Houser, D., Johnson, M., Kristensen, J., Lehnert, K., Lucke, K., Merck, T., Müller, S., Pawliczka, I., Ronnenberg, K.,

Rosenberger, T., Ruser, A., Tougaard, J., Schuster, M., Sundermeyer, J., Sveegaard, S., Wisniewska, D., and Siebert, U. (in press). "Impacts of underwater noise on marine vertebrates – Project introduction & first results," In A. N. Popper and A. Hawkins (Eds.) "The Effects of Noise on Aquatic Life" (Springer-Verlag).

Sundermeyer, J. K., Lucke, K., Dähne, M., Gallus, A., Krügel, K., and Siebert, U. (2012). "Effects of underwater explosions on presence and habitat use of harbor porpoises in the German Baltic Sea," In A. N. Popper and A. Hawkins (Eds.), *Effects of Noise on Aquatic Life*, (New York: Springer Science+Business Media, LLC), pp. 289-291 DOI 10.1007/978-1-4419-7311-5_64

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Other scientific publications

Dähne, M., Harder, K., and Benke, H. (2012). "Ergebnisse des Totfundmonitorings von Schweinswalen (*Phocoena phocoena*) an der Küste Mecklenburg-Vorpommerns im Zeitraum 1990-2010," *Natur und Naturschutz in Mecklenburg-Vorpommern*, **41**, 51-63.

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Erklärung

Hiermit erkläre ich, dass die vorliegende Dissertation selbständig von mir angefertigt wurde und in Inhalt und Form meine eigene Arbeit ist. Es wurden - abgesehen von der wissenschaftlichen Beratung durch meinen Betreuer - keine anderen als die angegebenen Hilfsmittel und Quellen verwendet. Die Arbeit wurde unter Einhaltung der Regeln zu guter wissenschaftlicher Praxis der Deutschen Forschungsgemeinschaft erstellt.

Diese Arbeit wurde weder ganz noch zum Teil schon einer anderen Stelle im Rahmen eines Prüfungsverfahrens vorgelegt. Dies ist mein erster Promotionsversuch. Die Promotion soll im Fach Zoologie erfolgen. Für die Prüfung wird die Form der Disputation gewählt. Der Zulassung von Zuhörern bei der mündlichen Prüfung wird nicht widersprochen.

Kiel, den

Michael Dähne