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First *in situ* passive acoustic monitoring for marine mammals during operation of a tidal turbine in Ramsey Sound, Wales

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ABSTRACT: The development of marine renewables has raised concerns regarding impacts on wildlife, and environmental monitoring is often required. We examined 3 mo of continuous passive acoustic monitoring (PAM) data collected at the Tidal Energy Ltd. DeltaStream turbine deployment in Ramsey Sound, UK. We aimed to assess the performance of the PAM system at an operational turbine, describe the 3D movements and behaviours of small cetaceans in the vicinity of the turbine, and model changes in detection rates against temporal and environmental variables. The PAM system was designed to acoustically detect, classify and track porpoises and dolphins via their vocalisations within a ~100 m radius of the turbine. In total, 247 small cetacean encounters were identified from click detections, which were also used to reconstruct the spatial movements of porpoises and dolphins, including close approaches to the turbine. Not all hydrophones were functional, which limited the ability to localise porpoise clicks; the probability of detecting and localising a click decreased by 50% at a range of ~20 m. Mechanical sounds on the turbine may have alerted cetaceans of its presence. In models examining acoustic detection patterns, the tidal state, time of day, low low-frequency noise levels and moon phase best explained the acoustic presence of porpoises. The limited duration of turbine operation yielded insufficient data to understand the effect of turbine rotation on animal presence and movement near the turbine. This is the first description of how small cetaceans behave and move around a tidal turbine, and we present recommendations regarding how PAM can be used to improve environmental monitoring at future tidal energy sites.

KEY WORDS: Marine renewables · Passive acoustic monitoring · Collision risk · Tidal energy · Environmental monitoring · Echolocation · Harbour porpoise

INTRODUCTION

Increasing concern over the threat of global climate change has prompted many nations to set ambitious renewable energy targets to reduce carbon emissions (Pelc & Fujita 2002). Tidal resources have been recognised as a sustainable, predictable and largely untapped source, and are expected to comprise a significant portion of clean energy contributions (Dolman & Simmonds 2010). Several in-stream

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tidal turbine projects around the world are in their early stages, many of which are proposed at large scales in the future (e.g. in the Pentland Firth, Scotland, and in the Bay of Fundy, Canada).

The potential for interactions between these new technologies and marine wildlife has raised conservation concerns for marine mammals (Inger et al. 2009, Boehlert & Gill 2010, Wilson et al. 2014), particularly the potential for animal injury or death from collision with moving turbine parts (Wilson et al. 2007). Other potential impacts include habitat loss due to the presence of the turbines and noise disturbance during operation (Frid et al. 2012), as well as indirect impacts such as reduced foraging opportunities in response to changes in prey distribution (Wood et al. 2013). Since only a handful of tidal energy projects are in operation, most impacts have not been adequately evaluated, and few have involved *in situ* measurement (Copping et al. 2014). Therefore, there is currently much uncertainty surrounding the nature and extent of any impacts of tidal energy devices on marine mammals, especially when considering the unknown cumulative impact of several turbines in an array (Sparling et al. 2016, Fox et al. 2018).

To address concerns of collision risk, there is a clear need to understand the fine-scale behaviours and movements of marine mammals around tidal turbines. Previous studies (e.g. Hastie et al. 2016, 2017, Macaulay et al. 2017, Waggitt et al. 2017a) have investigated marine mammal habitat use and behaviours in tidal areas in the absence of any tidal energy infrastructure. While such knowledge is relevant given that collision risk depends on animal density and diving behaviour (Hastie et al. 2014), these studies did not measure avoidance behaviour. Therefore, it is pertinent to monitor how animals move and behave around actual tidal devices, not just proposed tidal energy sites, and on a fine-scale, to fully understand the level of risk posed by these developments (e.g. Sparling et al. 2018). Understanding site-specific temporal trends in marine mammal presence and habitat use, in relation to environmental factors, is also relevant when considering collision risk (Cox et al. 2017).

Tracking marine mammal behaviour underwater can be logistically challenging at tidal rapid sites due to their high flow nature (Booth 2016, Fox et al. 2018). Marine mammals could be monitored visually, but this method is severely hampered by sea state and visibility (Booth 2016), and is not useful for determining how the animals are moving underwater. They could be tagged with sensors that record GPS, depth, orientation, and acoustics, and while this provides high quality behavioural information on an individual level, it is possible that a tagged animal would not spend much of its time in the small and select area of interest around a tidal turbine. Active acoustic monitoring is another possibility since it can track marine animals that either do not echolocate (e.g. seals), or that can echolocate but happen to be non-vocal (e.g. a silent porpoise; Hastie 2012). However, its range of observation is limited, as is its ability to identify detected animals to species (Hastie 2012). Porpoises and dolphins produce echolocation clicks to sense their environment and find food; these sounds can provide a means of detecting, locating and tracking these animals underwater in 3D via passive acoustic monitoring (PAM) (e.g. Hastie et al. 2006, Sparling et al. 2016, Macaulay et al. 2017). PAM, the method on which we focus in this study, is non-invasive, and is especially useful in recording the behaviour of vocalising animals when there is a single area of specific interest. PAM is recognised as a cost-effective method for environmental impact assessments around marine renewables (Dähne et al. 2013), and is appropriate for animals which spend most of their time underwater and click frequently, such as porpoises (Linnenschmidt et al. 2013).

Harbour porpoise *Phocoena phocoena* vocalisations are highly stereotyped narrowband high frequency (NBHF) echolocation clicks (–3 dB bandwidth of 16 kHz; peak frequency 130 kHz; Au et al. 1999) with source levels up to 205 dB re 1 $\mu Pa_{p\text{-}p}$ (peak to peak) (Villadsgaard et al. 2007). This makes them easily identifiable in UK waters where no other toothed whale produces NBHF vocalisations. Dolphins produce both clicks and whistles. Dolphin clicks are louder (up to 228 dB re 1 $\mu Pa_{p\text{-}p}$) and are broader in bandwidth (root mean square [RMS] bandwidths of 23–54 kHz; Madsen et al. 2004, Rasmussen et al. 2004, Wahlberg et al. 2011) than porpoise clicks. Species identification of dolphins based on single vocalisations is more difficult due to overlap in the acoustic characteristics between different species (Wood et al. 2013).

Here, we examined data from the first deploy-and-monitor study of small cetacean fine-scale movements at an operational tidal turbine in Ramsey Sound, Wales, UK. The Pembrokeshire marine area is a Designated Special Area of Conservation (SAC) that requires environmental monitoring. As part of the Collision Management and Adaptive Monitoring Plan (CMAMP) developed for a tidal turbine development in the UK, a PAM system was designed, comprising 12 time-synced hydrophones clustered into 4 groups of 3 hydrophones. This allowed for the detection, localisation, and fine-scale 3D tracking of the movements of vocalising porpoises and dolphins around the turbine. This study aimed to (1) assess the viability and performance of the PAM system at an operational turbine, (2) describe the 3D movements and behaviours of small cetaceans in the vicinity of the turbine, and (3) examine patterns in small cetacean presence at the marine renewable energy site by modelling changes in detections against temporal and environmental variables. This study reviews 3 mo of data from the first time a tidal turbine has been equipped with such a monitoring system anywhere in the world, and is therefore the first description of how marine mammals behave and move at an operational tidal turbine site, as measured by PAM.

MATERIALS AND METHODS

Tidal turbine and site

Tidal Energy Ltd. (TEL, Cardiff, UK) installed a DeltaStream in-stream tidal turbine on 13 December 2015, in North Ramsey Sound, Pembrokeshire, Wales, UK (51° 52.664′ N, 5° 19.473′ W), at a depth of ~30 m (Fig. 1). This ~1 km wide and ~3 km long tidal channel separates Ramsey Island from the west coast of mainland Wales. Ramsey Sound follows a semidiurnal tidal rhythm, with the stronger flood tide running approximately north. During spring tides, the tidal range is ~6 m and surface current speeds exceed 3 m s^{-1} (United Kingdom Hydrographic Office 1999).

The DeltaStream unit was gravity-mounted on the seabed, on a triangular steel base supporting one 3-blade turbine (Fig. 1). The device was connected to shore via a submarine cable. A hydraulic yaw mechanism controlled the turbine orientation in relation to flow direction. The turbine operated periodically during this commissioning phase, and on occasion the blades were rotated without engaging the turbine gears. Here, all rotating times are considered together, whether generating or not. When the turbine was not rotating, a brake was applied and the turbine was rotated ~90° across the current.

Small cetacean monitoring

Dolphin species that may be present in Ramsey Sound include: bottlenose dolphin *Tursiops truncatus*, Risso's dolphin *Grampus griseus*, short-beaked common dolphin *Delphinus delphis*, Atlantic white-sided dolphin *Lagenorhynchus acutus* and white-beaked dolphin *L. albirostris*.

Passive acoustic monitoring

The PAM system consisted of 12 hydrophones mounted on the upper surface of the triangular base of the DeltaStream (5 m below the centre of the turbine). The hydrophones were mounted in 4 clusters of 3 hydrophones each (manufactured by Seiche). A single cluster was capable of measuring bearings to received sounds, and range determination was possible if sounds were received on multiple clusters. Fig. 1 displays the positions of the clusters, with hydrophones within each cluster (0.2 m apart) arranged in an equilateral triangle formation. Triad clusters of hydrophones were spaced at varying distances from one another (7.9, 14.28 and 14.76 m) along the triangular turbine base.

Data from the hydrophones were digitised on the turbine using a National Instruments (NI) cDAQ-9188 Compact Data Acquisition chassis equipped with 4 NI 9222 analog–digital conversion modules. The NI chassis was configured to sample all channels at 500 kHz. The chassis also contained a single NI-9264 analog output module to control the gain and filter settings of hydrophone preamplifiers. The chassis was connected to shore via a dedicated optical fibre, within the main DeltaStream communications and power cable.

Post-installation testing showed that only 7 of the 12 hydrophones were working (Fig. 1), and of these, only 5 (hydrophones 1, 4, 5, 10 and 11) were fully functional across the entire range of frequencies, with 2 of them (hydrophones 2 and 7) not picking up high-frequency harbour porpoise clicks, but picking up broadband dolphin clicks. This limited the localisation ability of the PAM system. The reasons for these failures is not yet known since the turbine has not been recovered. The 7 working hydrophones of the PAM system collected acoustic data from 16 December 2015 (15:34:43 h) onwards, until 6 March 2016 (04:00:00 h), for a total of 1932.42 elapsed hours (80.52 elapsed days), at which point both turbine operation and data collection ceased.

Visual monitoring and flow speed measurement

The CMAMP also required shore-based visual observation whenever the turbine was rotating, with

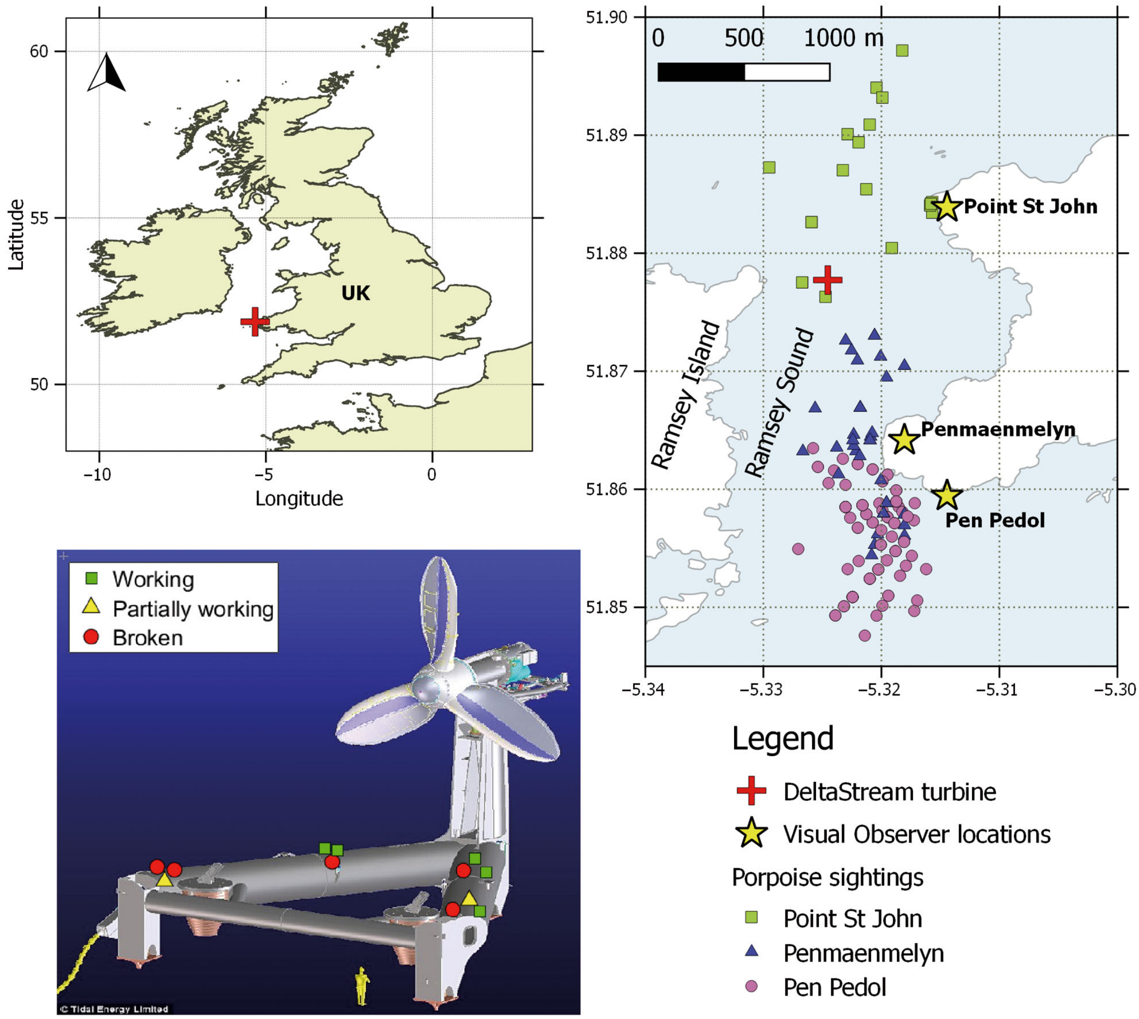

Fig. 1. DeltaStream turbine (from: http://tidalenergytoday.com), and map of its deployment location in Ramsey Sound, Wales, UK, with locations of visual observations of porpoises. Hydrophone locations and their operational status are also shown on the turbine. Hydrophones were either operational, partially operational (operational in dolphin frequencies but not in higher porpoise click frequencies) or broken on the turbine-mounted passive acoustic monitoring system

the exception of poor sighting conditions due to weather and sea state. These were carried out by M. G. Barradell (Tidal Energy Ltd. pers. com.) at 3 sites: Pen Pedol (51° 51.57′ N, 5° 18.87′ W), Penmaenmelyn (51° 51.85′ N, 5° 19.08′ W) and Point St John (51° 53.03′ N, 5° 18.87′ W), the site closest to the turbine (Fig. 1). An on-site acoustic Doppler velocimeter (ADV) recorded flow speeds.

PAM analysis

Data collection and analysis was conducted using the open-source PAMGuard software (www.pamguard.org, Gillespie et al. 2008), which can directly control and acquire data from the NI chassis and process data in real time to detect odontocete sounds. A second watchdog program ensured that PAMGuard was running, restarting it automatically should it have stopped working for any reason.

Detection and classification

PAMGuard was configured to detect both clicks and tonal sounds, such as whistles, and continuously calculate noise levels in octave frequency bands. The PAMGuard click detector was configured to detect clicks with energy in the 25–170 kHz frequency band with a detection threshold set to 8 dB above background noise levels. All detected transients were then classified as unknown, porpoise or generic dolphin, using the PAMGuard click classifier. A dolphin whistle detector (Gillespie et al. 2013) was run on acoustic data decimated to 50 kHz, also with an 8 dB trigger threshold. All detected clicks and whistles were recorded and saved as PAMGuard binary files; however, due to the high volume and sampling frequency of the acoustic data, only 10 s of continuous raw data were recorded every hour. All detection algorithms were run in real time, and summaries of acoustic data were automatically sent to the central turbine supervisory control and data acquisition system (Bromley et al. 2015). This could alert observers in the on-shore control room of possible acoustic encounters.

The PAMGuard offline viewer was used post-data collection to manually confirm real-time detections, and to check clicks that may have been misclassified during the initial real-time analysis (false negatives, which were then added) as well as for clicks which were incorrectly included by the automated analysis (false positives, which were then removed). Clicks were considered to be part of an 'encounter' if there were at least 5 classified clicks spaced closely in time to one another (in part of a click train). If these groups of clicks were spaced <10 min of one another, they were considered to be part of the same encounter, and manually assigned as such. Ten minutes was also the minimum period in which tidal flow could change by 10%. Thus, 10 min was considered an appropriate balance between change in tidal flow and continuous acoustic encounter duration, most of which were <10 min.

Localisation

Clicks identified as originating from harbour porpoises or dolphins were localised using the PAMGuard Larger Aperture 3D Localiser module, using a time-delay based 'Mimplex' algorithm described by Macaulay et al. (2017). Tidal environments are often noisy, reverberant and can contain multiple echolocating animals. This can result in particularly complex soundscapes in the porpoise and dolphin frequency bands, which makes matching the same echolocation signals on different hydrophones difficult. The Mimplex algorithm calculates all possible combinations of detected clicks that might match across different hydrophones. It then selects the most likely combination and uses a Markov Chain Monte Carlo (MCMC) simulation to localise and accurately propagate errors in sound speed and time delay measurements to the position of an animal.

For error estimation, the Mimplex algorithm assumed standard errors of 10 m s^{-1} in sound speed, a liberal estimate based on previous surveys in tidal streams (Macaulay et al. 2017). Measurement errors in hydrophone positions were estimated to be 2 mm in hydrophone locations within clusters and 2 cm between different clusters. In a precisely engineered structure such as a tidal turbine, these measurement errors are likely to be overestimates. The localisation algorithm cross-correlated porpoise signals as recorded on different hydrophones to calculate time of arrival differences. Porpoise clicks are relatively long (100 µs; Au et al. 1999) and narrowband, and so a cross-correlation function between 2 signals results in many peaks of similar magnitude. Due to noise, signal distortion and/or distribution of sampling bins, the correct peak (corresponding to the correct time delay measurement) can be slightly lower in magnitude than the previous or subsequent peaks. We assumed that half of the time, peaks from the cross-correlation function were picked correctly, and the other half of the time, an incorrect cross-correlation peak (from the immediately subsequent or previous peak) was used, which would introduce a time delay error. This results in a standard deviation error of 3.84 µs in time delay measurements (rounded to 5 µs), included as an average time-delay error in the localisation algorithm. With fewer (only 5) hydrophones functional in the porpoise frequency range (Fig. 1), localisations of porpoise clicks were limited, but still possible.

After detection-matching and successful localisation, the quality of resulting positional information is dependent on both the location and number of hydrophones ensonified. At least 3 widely spaced hydrophones are required for a 2D localisation and 4 hydrophones distributed in 3D are required for a 3D localisation (Wahlberg et al. 2001). The close spacing of the hydrophones within each cluster (Fig. 1) meant that a single cluster could resolve a bearing to a vocalising animal, but not a range. When multiple widely spaced clusters were ensonified, the bearings from different clusters would cross at the location of the vocalising animals and a range could be calculated. In other words, more than 1 hydrophone cluster had to be ensonified for a click to be localised, and this was not necessarily the case for every click in a click train. Since the hydrophones were mounted in a plane, all localisations were subject to an up-down ambiguity across the plane of the hydrophones, but since these were close to the seafloor, we assumed that the localisations occurred above this. Additional data plots and visualisations of tracks were created in MATLAB (The Mathworks).

To investigate the fine-scale movements and behaviour of echolocating animals in the vicinity of the turbine, animal tracks were generated from consecutively occurring localised clicks. This could not be done for encounters that did not contain any localisable clicks. Localisation results for each encounter were filtered so that clicks that were distant (>150 m), above the sea surface, or were likely echoes were excluded from the track. Localisations were further inspected manually to visualise a time series of the angle, vertical and horizontal range of the animal to array, as well as a top-down view of localised clicks.

Localisation accuracy and probability function

A simulation module within PAMGuard was used to simulate animals distributed in a 100 m × 100 m × 15 m grid around the DeltaStream to model the localisation accuracy as a function of distance and bearing from the hydrophones. Clicks were simulated at each 5 m interval in the grid and localised with an MCMC-based localisation algorithm, using the same error estimates, as above. The MCMC algorithm calculated accurate error estimates for each grid point, allowing an error surface around the array to be calculated.

A localisation probability function was created in DISTANCE software (http://distancesampling.org/, St Andrews, UK). We were not able to construct a true detection function of clicks as ranges were only available for localised clicks (not for all detected clicks). The localisations that contributed to this function were those with range <200 m from the mean location of the hydrophones. Point sampling (appropriate for the static PAM system) and radial distance options were selected to correct for a greater sampling area at further distances, and the localisation probability function was fitted with a half-normal distribution.

Noise analysis

Noise measurements were continually made from recordings using the PAMGuard noise band monitor module. Octave-band noise levels, between 0.177 and 181 kHz (based on mean absolute noise levels in every 6 s period throughout the deployment period; see Table S1 in Supplement 1 at www.int-res.com/articles/suppl/m590p247_supp/), were measured. Short WAV file recordings (10 s h^{-1}) of the full bandwidth (500 kHz) data were saved.

Explanatory variables modelling

To examine patterns in porpoise presence at the tidal turbine site, generalised additive modelling-generalised estimating equation (GAM-GEE) models were fit to the data following methods of Pirotta et al. (2014) and Booth et al. (2013). We investigated changes in porpoise detection probability against a variety of temporal and environmental factors as explanatory variables (Booth et al. 2013, Booth 2016). The model used the presence or absence of porpoises (as indicated by encounters) detected by the PAM system as the response variable (as was done by Wood et al. 2013). Only acoustic encounters with porpoises were included in the models due to few dolphin encounters (Table 1).

Candidate explanatory variables were grouped into 3 categories: those that described (1) tidal state, (2) light levels and (3) noise levels (Table S2 in Supplement 1). Tidal state variables considered included (i) flow speed (m s^{-1}), (ii) tidal height (m), (iii) ebb or flood (binary), (iv) spring/neap (binary) and (v) a continuous measure of position in the tidal cycle. This was a circular variable that divided each ebb and flood into 36 time increments (i.e. 72 'tide-indices') with each time window approximately 10 min long (range: 9.9 to 11.1). Time windows were counted from 1, corresponding to the first increment after a change from an ebb to a flood tide, to 72,

Table 1. Summary of number and duration of porpoise and dolphin acoustic encounters across 75.58 d in which the passive acoustic monitoring (PAM) system was operational. Days: porpoise- or dolphin-positive days; Duration: duration of an encounter (mean ± SD, shown as mm:ss); Total: total duration of the encounters; %Time: percent of the entire recorded time containing such encounters; Rate: hourly encounter rate

Species	Encounters (n)	Days	Duration (min–max)	Total (hh:mm:ss)	%Time	Rate
Porpoise	236	69	03:37 ± 04:40 (00:01–35:03)	14:14:52	0.78	0.130
Dolphin	11	10	12:09 ± 11:18 (00:01–31:26)	02:13:44	0.12	0.006

corresponding to the final ebb increment before turning to a flood tide. Variables that described light levels were (i) daylight/darkness (binary), (ii) a continuous circular variable between 0 and 24 that wrapped around a 24 h clock ('time of day'), (iii) hour of day, (iv) a continuous measure of moon luminance (1 = full moon, 0 = new moon). Noise variables included (i) noise band levels within selected octaves averaged within each 10 min increment and (ii) an indicator variable denoting whether the turbine was rotating.

Flow speeds recorded by the ADV were processed into 1 min time-averaged summaries across the depth range of the rotor disc. A non-parametric kernel-smoothed relationship between tidal flow and current speed was fit to build a sinusoidal cosine function used to interpolate missing flow speed data (5.91 d of flow data were missing from the ~3 mo deployment period).

Tidal heights were obtained for nearby Milford Haven (www.tidetimes.org.uk). Slack water at Ramsey Sound occurs 3 h after high and low water in Milford Haven (P. Bromley pers. comm.), so tidal heights for Milford Haven were offset by +3 h; these were confirmed as appropriate by examining the relationship between measured flow speed at Ramsey Sound, and calculated tidal height. Sunrise and sunset times for Ramsey Sound were obtained from http://aa.usno.navy.mil/data/docs/RS_OneYear.php.

Noise measurements in 2 different octave bands were included in the model. The first band (0.7 to 1.4 kHz) was included in order to study how animals may be reacting to low-frequency noise generated by the turbine. The second band (90 to 180 kHz) was included to assess PAM performance, as variation in noise levels in this frequency band, which overlapped in frequency with the bandwidth used for click detection, could affect the system's detection function. Thus, including this high frequency band within the model allowed us to account for potential variation in the acoustic detectability of porpoises.

Our model assumed a binomial distribution with a logit-link function for modelling the presence or absence of porpoise detections for each 10 min period. The GEE structure within the GAM-GEE framework permits the inclusion of an AR(1) autocorrelation matrix to account for the significant temporal autocorrelation observed in the model residuals. The GAM framework allows for the flexibility of including cubic *b*-spline transformations of regression variables where model fit penalty criteria support this complexity. The number of knots used in our models was determined heuristically by matching the flexibility of the spline to the observed pattern in the raw data with equally spaced knots (Wood 2003).

We took several steps to avoid unstable parameter estimates, inflated standard error estimates and possible bias in model inference that can arise from multicollinearity in covariates. We used forward selection to build the statistical model using R packages 'geepack' (Halekoh et al. 2006), using a quasi-likelihood information criterion (QIC) for GEEs as an information criterion balancing goodness of fit and model complexity for GEE models (Pan 2001). In the first step, we fit univariate models using each candidate variable (Table S2 in Supplement 1), selecting the model with the lowest QIC/QICu. We then fit 2-variable models by selecting the regression variable from the first step, and adding 1 variable from each of the 2 other variable categories. The model with the lowest QIC/QICu was again selected. A 3-variable model was then fit selecting from the third regression variable category still not represented in the model. The final step was to sequentially add and remove all the variables to the 3-variable model across the 3 variable categories to see if the model fit statistic could be improved (Table S2). In this step, we examined the generalised variance inflation factors (GVIFs), and highly co-varying predictive variables (GVIF < 5, Menard 1995) were not included in the same model. The model with the lowest QIC of all candidate models was selected as the final model.

For regression parameter estimation, we used the GEE sandwich variance estimates, as parameter estimates are consistent even when the covariance structure is mis-specified. Different models with all combinations of variables were fitted, with the best model selected using QIC goodness of fit statistics. All statistical analysis was performed in R (v. 3.3.2, R Core Team 2016).

RESULTS

Assessment of PAM system performance

Reliability

The PAM system collected data nearly continuously over the period of operation. A total of 1813.96 h (75.58 d) of PAM data were collected. As such, from start to end of the monitoring period, the working hydrophones of the PAM system collected data for 93.9% of the deployment period. There were 3 consecutive days when data were not collected, which was caused by the PAMGuard configuration file on the PAM computer being accidentally moved. Excluding this gap, the PAM system collected data for 99% of the deployment period.

Noise

Metal flaps, which covered entrance holes to the turbine in order to reduce the inflow of silt, produced regular loud clanging noises with most of their energy below 1 kHz (Fig. 2), which lies in the 0.7–1.4 kHz noise band used in models on porpoise presence described above. There was almost no energy above 5 kHz, so these low-frequency sounds did not interfere with click detection. WAV recordings revealed the presence of several clangs, spaced at varying times from one another and at different intensities, often preceded by a higher-pitched moan, potentially originating from the metal flap hinges (an example can be heard in Audio S1 at www.int-res.com/articles/suppl/m590p247_supp/). The relationship between clang rate and tidal state could not be examined because of the way in which the WAV recordings were triggered.

The clangs had a measured received level (RL) of 176 dB re 1 µ$Pa_{p\text{-}p}$ on a hydrophone in a cluster closest to the turbine. The source level (SL) could not be defined because the origin was unclear and sound transmission to the hydrophones could have been through the steel of the turbine support structure as much as through the water. However, if the assumption is made that the clang originated somewhere on the turbine (as opposed to on the base), a back-calculated SL ranging from 185–198 dB re 1 µ$Pa_{p\text{-}p}$ results, with this range encompassing both the extremes in sound source position (range from receiving hydrophone to the closest point vs. farthest point on turbine), and the extremes in transmission loss (cylindrical vs. spherical spreading). This sound would be clearly audible to porpoises, as the RL is ~96 dB above the porpoise auditory threshold (~80 dB re 1 µPa) at this frequency (Kastelein et al. 2002).

Another distinctive mechanical source of noise came from the hydraulic pumps used to rotate the turbine into the current; this action occurred 26 times during this 3 mo period. This infrequency, and the short duration (several seconds per occurrence) of this action, meant that the pumps contributed little to average noise levels. This action was, however, clearly audible at times it did occur. These sounds caused false whistle detections (which were removed during manual event validation) at a frequency of ~13 kHz, and were outside the 2 noise bands used in modelling.

The 90–180 kHz octave band was dominated by tonal electrical noise at 100 kHz. This was internal to the turbine electronics, which we believe originated in the turbine power supplies. Since this tone was within the electrical system, it would not have been audible to any animal as it did not exist as a pressure wave in the water. However, the elevated noise level severely hampered our ability to detect animals. This noise was highly constant, regardless of whether the turbine was rotating or not, and was at a level of 0.046 V_{RMS} at the input to the digitising electronics, equating to a sound pressure level of 132 dB re 1 µPa_{RMS}. Overall, noise levels in the detection band rose by about 3 dB as tidal flow increased from 0 to 2.5 m s^{-1}. However, we do not believe that this had a significant effect on the number of animals detected at high flow rates for the following reasons:

(1) Apart from the constant electrical signal, other noises were highly intermittent. Since the detector has a threshold settling time of ≪1 s,

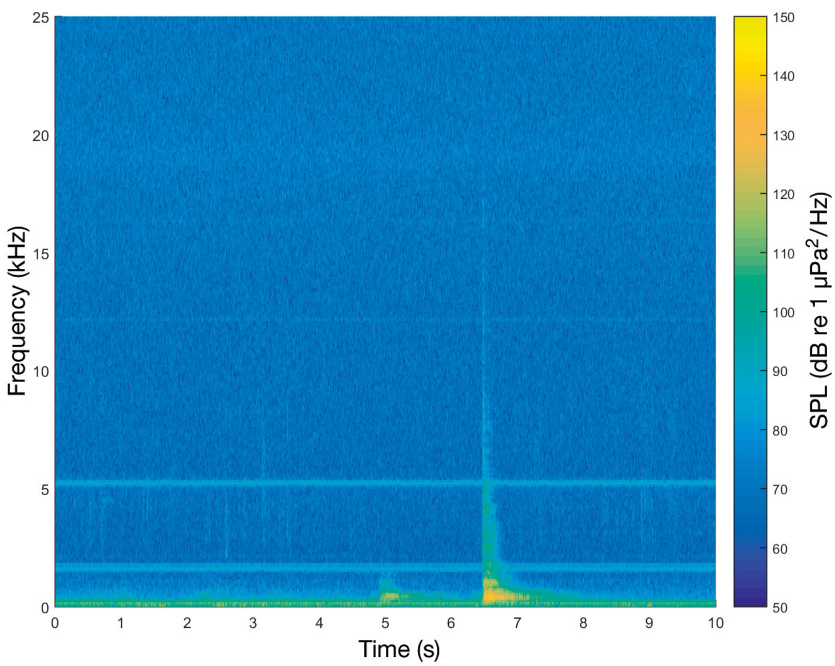

Fig. 2. Spectrogram of a clang from a metal flap on the DeltaStream, shown at ~6.5 s into the file (FFT length = 512, Hann window, 50% overlap). The colour bar indicates the sound pressure level (SPL; dB re 1 µPa^2/Hz)

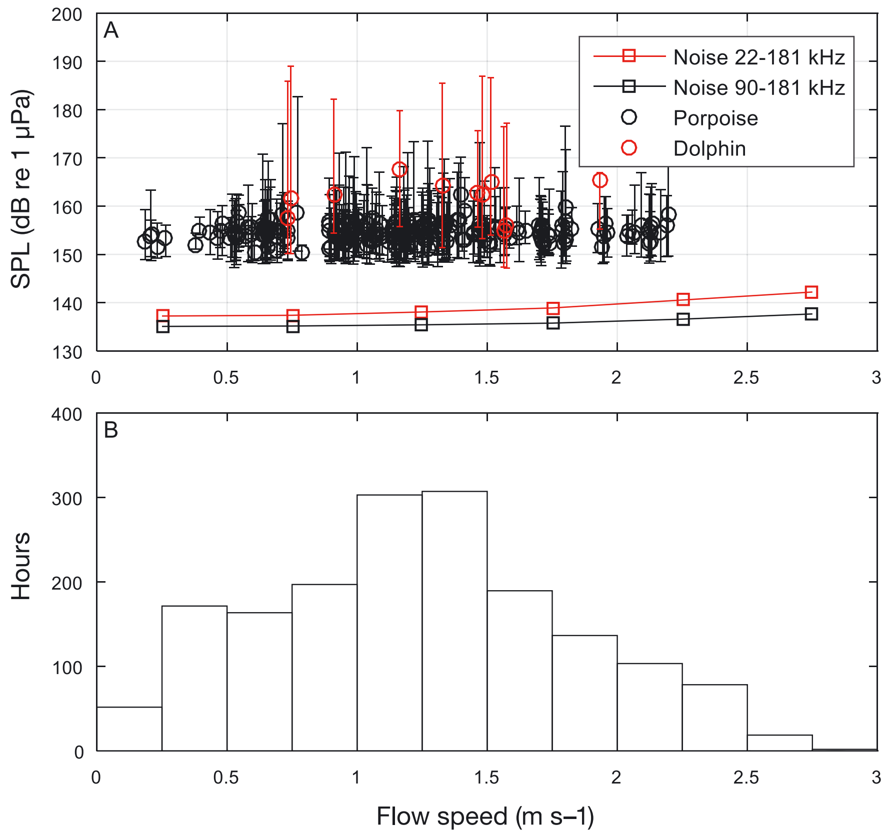

Fig. 3. (A) Peak to peak received level of detected porpoise and dolphin clicks, within each event as a function of tidal flow. Circles represent the median amplitude of the clicks in each encounter, and the vertical 'error' bars show the minimum and maximum amplitudes of clicks within each encounter. These are shown alongside median noise levels for the 22–181 and 90–181 kHz detection bands which represent the detection trigger frequency band and the frequency band most important to porpoise click classification, respectively. SPL: sound pressure level. (B) Number of hours of operation at each tidal flow rate

clicks could still be detected between these transient noises.

(2) Although some individual clicks may have been missed at high flow rates, the probability of retaining at least some clicks in an event is always greater than the probability of retaining individual clicks, i.e. the quieter ones or ones which coincide with an intermittent noise may be lost, but the event is not. Fig. 3 shows the amplitude range of detected clicks in every porpoise event as a function of tidal flow, along with the RMS noise levels in the 22–181 kHz and the 90–181 kHz frequency bands. The amplitude of the quietest clicks detected at each tidal flow remains more or less constant, and all events also have clicks at amplitudes several dB higher than the quietest clicks.

A composite of noise band levels within each octave band over the 3 mo period is shown in Fig. 4, with overlaid turbine rotation periods and animal acoustic encounters. Regular peaks in many bands show noise level variation across the tidal cycle. Peaks in noise levels can also be seen during periods of turbine rotation, particularly in octave bands <1.4 kHz. Note that the highest noise band (90.5–181 kHz) contains the constant 100 kHz tone within the turbine electrical system (Fig. 4).

Fig. 5 shows the estimated on-axis detection range of 3 reported harbour porpoise click SLs (Villadsgaard et al. 2007, Kyhn et al. 2013). This assumed a simple spherical propagation model ($20\log_{10}(R) + 0.0045R$, where R is range; Ainslie & McColm 1998). Given an 8 dB click detector threshold above background noise of 135 dB re 1 µPa$_{RMS}$, this gave an equivalent absolute detection threshold of 143 dB re 1 µPa$_{RMS}$. The highest porpoise SL measurements may still give a range (for on-axis clicks) of up to 200 m (Fig. 5). However, more typical detection ranges are likely to be reduced — due to off-axis click detection, and varied porpoise behaviour and SL — to a few 10s of metres.

Localisation accuracy and probability function

Modelled error surfaces of the localisation accuracy of the PAM system, created for 12, 7 and 5 working hydrophones (Fig. 6) show that dropping from 12 to 7 hydrophones significantly reduced how accurately the range to animals could be estimated. With only 5 working hydrophones (as was the case for clicks at porpoise frequency), errors were non-uniformly distributed and could approach the 10s of metres, even very close to the array.

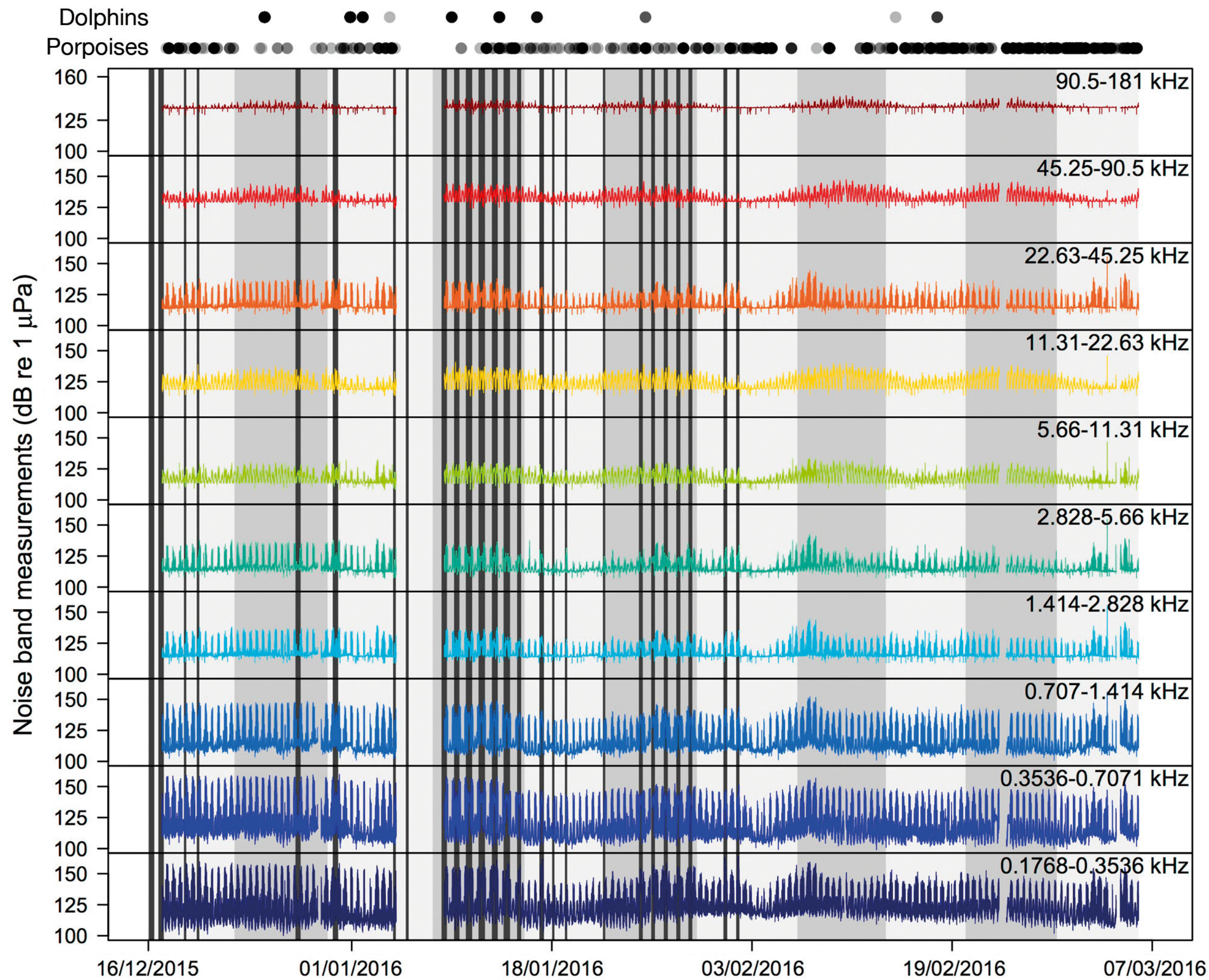

Fig. 4. Noise band measurements for each octave-level frequency band. Spring (mid-grey) and neap (light grey) cycles are in the background. The circles at the top show when porpoises and dolphins were detected via passive acoustic monitoring (note that superimposed circles give the effect of different grey shades). Vertical dark grey bands show when the turbine was rotating, with thicker bands indicating the turbine was rotating for longer

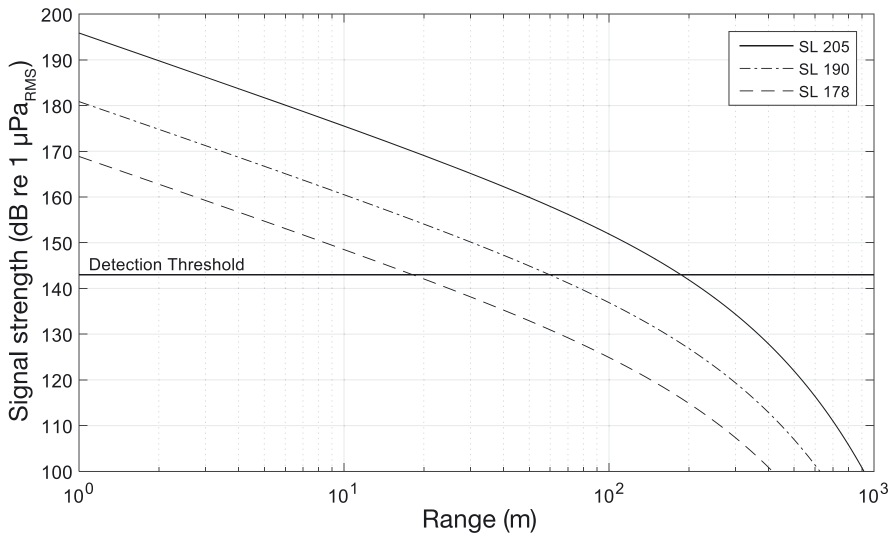

Fig. 5. Signal strength of porpoise clicks as a function of distance for 3 different estimates of wild harbour porpoise click source level (SL). Note that SLs are quoted in dB re 1 μPa$_{p\text{-}p}$, but the plots show root mean square (RMS) levels, which give a better prediction of detection capability. The detection threshold of 143 dB re 1 μPa$_{RMS}$ is based on the detection threshold being 8 dB louder than the typical noise level of 135 dB re 1 μPa$_{RMS}$ in the click detector band

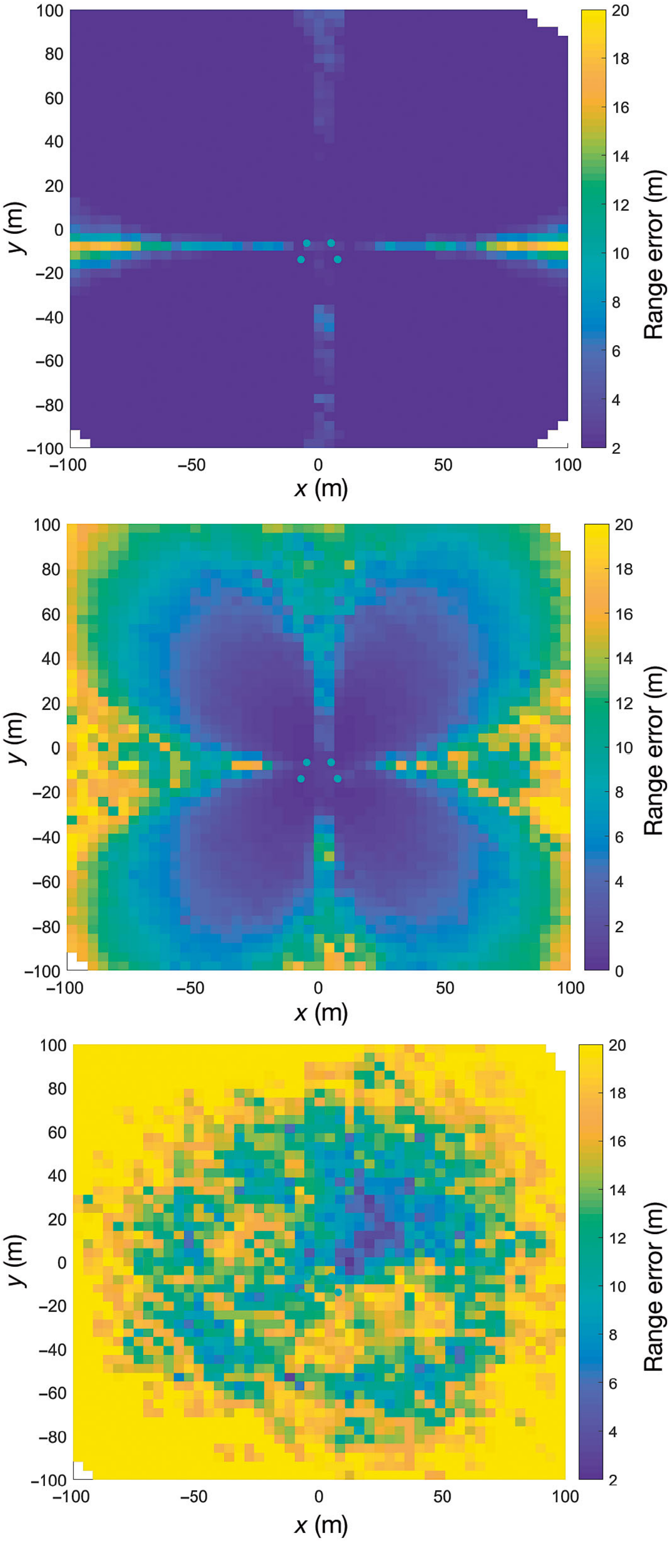

Fig. 6. Predicted range error surfaces for hydrophone arrays of (A) 12, (B) 7 and (C) 5 hydrophones, where (0,0) is the location of the turbine. Note the dramatic increase in range errors with fewer hydrophones. Each scenario is averaged over 5 m depth bins. Turquoise points represent the locations of each of the 4 hydrophone clusters

The probability of being able to detect and localise a click decreased by 50% at a range of ~20 m from the turbine base (Fig. 7). Comparable results were also obtained for dolphin clicks, as well as for when porpoise localisations were split into day and night. A day–night comparison for dolphin clicks was unavailable since all encounters occurred at night.

Small cetacean detections

Summary of porpoise and dolphin detections

Both harbour porpoises and unidentified dolphin species were acoustically detected. Table 1 shows the total number and duration of encounters. Of the full 75.58 d over which the PAM system was operational, there were 69 porpoise-positive days (91.3%) and 10 dolphin-positive days (13.2%), with an average of 3.13 acoustic animal encounters detected each day. The first animal encounter recorded by the PAM system was a porpoise; it occurred 28 h, 44 min after the initial PAM connection time. There were 2 instances in which porpoise and dolphin encounters overlapped. No dolphin encounters included whistles. Most detected encounters (71% of dolphin encounters, and 91% of porpoise encounters) occurred during hours of darkness. More detected porpoise encounters occurred during both neap and ebb tides (66%) than during spring and flood tides. Distributions of encounter data as a function of tidal current velocity, tidal state and turbine rotation are shown in Fig. 8. At the turbine site, the flood tide (maximum flow ~2.9 m s^{-1}) was characteristically stronger than the ebb tide (maximum flow ~1.6 m s^{-1}).

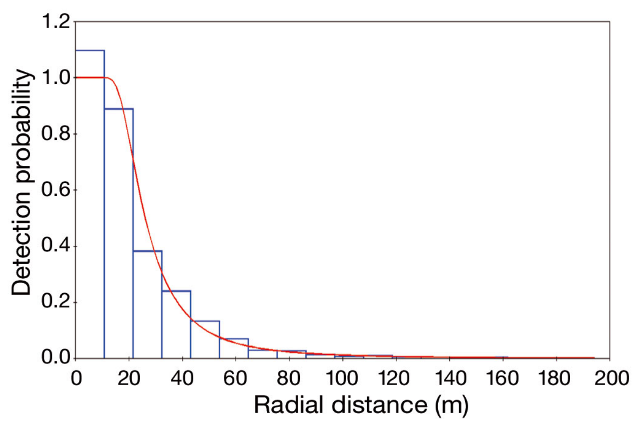

Fig. 7. Localisation probability function of porpoise clicks, as determined using 5 functional hydrophones at the tidal turbine site. Bin size = 10.8 m

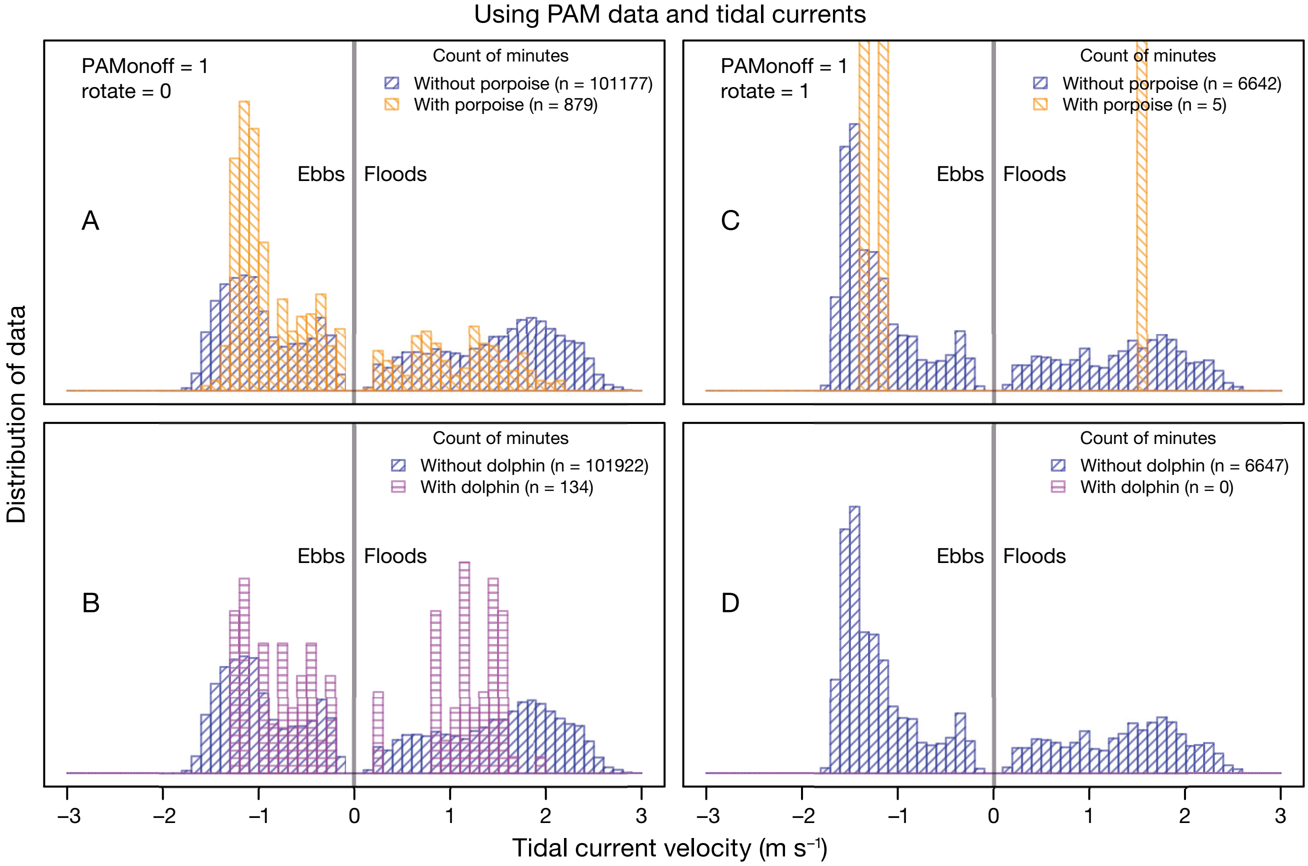

Fig. 8. Distribution of (A,C) porpoise and (B,D) dolphin data where each minute of each encounter is included as a function of tidal current velocity, tidal state and turbine rotation. A,B: turbine off; C,D: turbine on

As this testing period for trialling the PAM system was also the commissioning period for the DeltaStream, the turbine was only rotating for 6% of the survey period (Table 2). There was one 2 h period in which the PAM system was off and the turbine was rotating; otherwise, the PAM system was recording when the turbine was rotating. There were 4 instances of harbour porpoise acoustic encounters and no instances of dolphin encounters during periods of turbine rotation.

Shore-based visual observations were limited by weather, observation effort was sporadic, and only 22% of effort occurred at the location (Port St John) overlooking the turbine site. There were few visual detections (3 porpoises, 0 dolphins) during periods of turbine rotation (Fig. 9). Only visual observations from Port St John are shown in Fig. 9, but note that these include visual observations >1 km from the turbine. Only 2 visual observations of porpoises occurred within 500 m of the turbine location, but this only occurred when the turbine was not rotating. PAM detections (comprising 4 events) were recorded when visual effort was ongoing in daylight and nothing was seen by the observer based at the location closest to the turbine (Fig. 1).

Table 2. Review of time (h) in which the passive acoustic monitoring (PAM) system and turbine rotation were on or off

		PAM system On	PAM system Off	Total
Turbine rotation	On	124.5	2	126.5
	Off	1689.46	116.45	1804.9
Total		1813.96	118.45	1932.4

Small cetacean movements and behaviours in turbine vicinity

The best 2 examples of small cetacean tracks in the vicinity of the turbine are shown in Fig. 10 (also see Fig. S1 in Supplement 1). One porpoise event occurred during a low-flow period at low water, in

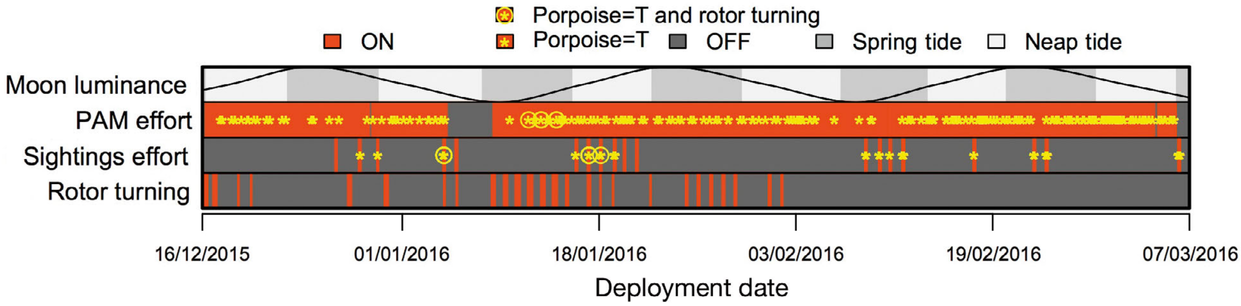

Fig. 9. Porpoise detections in relation to passive acoustic monitoring (PAM) and visual observer effort. The top panel shows the spring/neap cycles, with the black line showing the moon luminance. The second panel shows PAM effort (red = on, grey = off), with the 3 yellow circles indicating instances where the turbine was rotating and porpoises were detected with PAM. The third panel indicates sighting effort and sightings of porpoises, at the observer locations closest to the turbine site, with 3 yellow circles indicating when the rotor was turning and porpoises were visually observed. The final panel shows the 26 days when the turbine rotor was spinning (red = on)

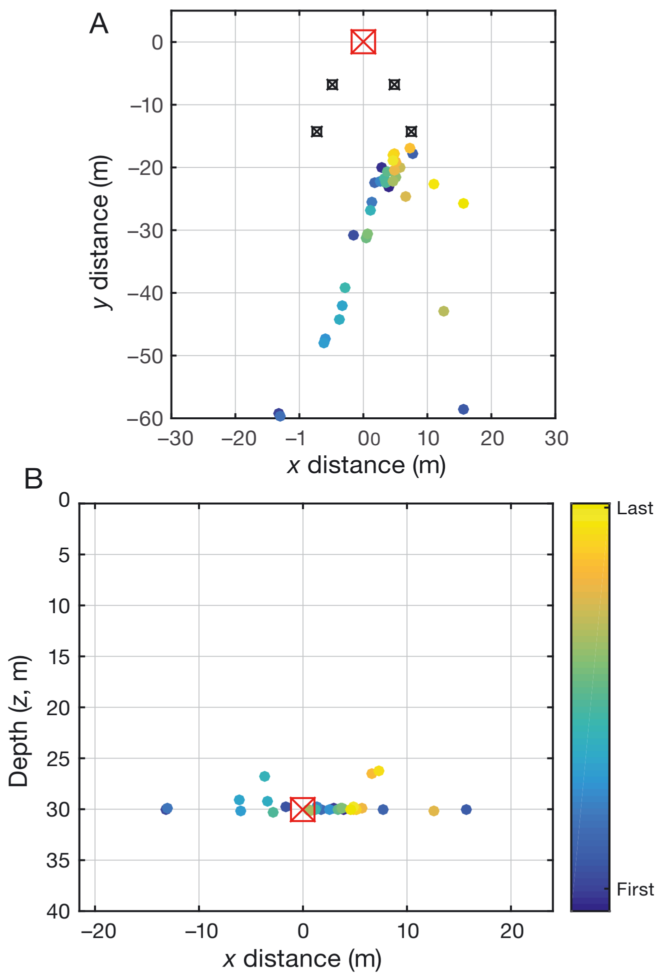

Fig. 10. Example of a porpoise encounter. Tracks of porpoise movement, as constructed from localised clicks, are displayed from (A) a top-down (x,y) view and (B) a depth-profile view (x,z), and are coloured by order in time. The location of the turbine is marked with a red box at (0,0). In the upper panel, the locations of the hydrophone clusters are marked with black crossed boxes

a spring tide, when the turbine was not rotating, in non-daylight hours. Here, an echolocating porpoise moved towards the turbine platform at a constant depth, and then changed direction by over 90° once it reached the platform (Fig. 10). Note that the track approaching the hydrophone array extends farther out than the outgoing track, with RLs increasing as the porpoise approaches and decreasing as the porpoise swims away. Echolocation clicks are primarily forward-projecting, but can still be recorded off-axis, especially at close range. In a tidal flow, note that the orientation of the porpoise (heading) is not necessarily the same as the direction of movement (course over ground). There is no raw WAV recording during this ~2 min encounter to confirm whether mechanical clanging was occurring at this time, but an available recording 5 min prior contains a clang.

Secondly, a dolphin event shows a close approach, with a dolphin(s) passing near the turbine, during a low-flow period at low water in a neap cycle, when the turbine was not rotating, in non-daylight hours (Fig. S1 in Supplement 1). Some clicks have not been accurately localised, causing scatter across the plots of clicks which do not form part of a track. A dolphin buzz sequence (echolocation clicks closely spaced in time, interclick interval < 10 ms) occurred within this same event. During this <1 s period, a dolphin rapidly echolocated on 1 hydrophone cluster while approaching it, at a height of <1 m above it.

Finally, of the 4 porpoise encounters that were detected during periods of turbine rotation, only 1 produced >10 localised clicks. This encounter occurred during an ebbing spring tide. In this instance, a porpoise approached the turbine at the

Table 3. Retained concordance correlation coefficients (CCC) for significant covariates retained in the generalised additive modelling-generalised estimating equation (GAM-GEE) model, with the *b*-spline degrees of freedom, Wald chi-squared statistics and p-values for the predictive covariates in the statistical model of porpoise detections. Covariates are listed in order of importance. Note that CCC is a measure of the total variability in the dataset that can be attributed to the 'true' variance from each predictor. The remaining unaccounted variability is attributed to model error

Retained covariate	CCC	df	χ^2	p
Tidal cycle (across 10 min increments for a full ebb/flood cycle)	8.8	4	131.7	<0.001
Noise level (in 0.7–1.4 kHz band)	1.9	3	34.4	<0.0001
Time of day (24 h clock)	1.1	2	14.6	0.0007
Moon luminance	0.5	3	11.6	0.0093

depth of the turbine centre, but not closely (minimum distance of 15 m from the turbine centre), staying outside of the triangular base of the DeltaStream. The accompanying track of this encounter is limited due to few localised clicks.

Patterns in acoustic detections in relation to environmental variables

Four covariates with the greatest predictive power were retained in the final GAM-GEE model. The significance of each covariate was tested using a Wald chi-squared test (Table 3). These included tidal cycle, noise levels in the lower frequency noise band (0.7–1.4 kHz), time of day and moon luminance (Table 3). The low sample size of acoustic encounters during turbine rotation led to the binary variable of turbine rotation being dropped as a model covariate.

Model results are shown graphically in Fig. 11. The presence of porpoises, as indicated from passive acoustic encounters, was stronger during the ebb tide than during the flood tide. Porpoise presence was lowest during peak flow in either ebbing or flooding tidal state. Acoustic detections of porpoises were also more common in the early hours of the day (~04:00 h), and least common in the afternoon (~16:00 h). Acoustic detections of porpoises were greater during periods with lower noise levels in low frequencies (0.7–1.4 kHz). Moon luminance was also retained as a predictor of porpoise presence, with more encounters detected when the moon was fuller.

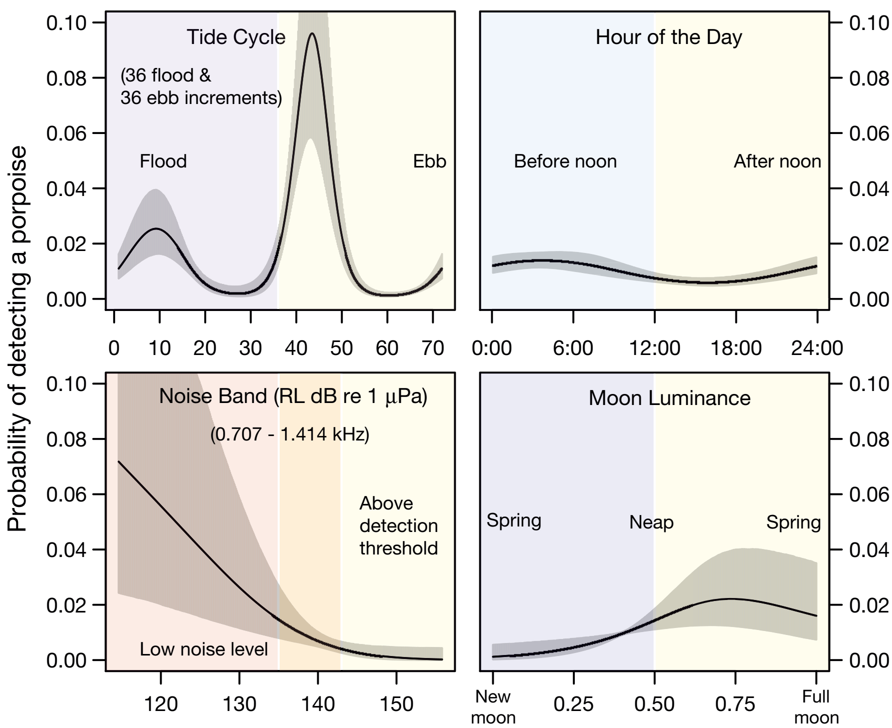

Fig. 11. Generalised additive modelling-generalised estimating equation (GAM-GEE) model results of acoustic detections of porpoises as a function of tidal cycle indices, time of day, low-frequency noise levels, and moon luminance. The smoothing function estimators and 95% confidence intervals are plotted for each of the covariates showing the correspondence to the probability of detecting a porpoise. The acoustic detections are most likely to occur during ebb tides, between the hours of midnight and 06:00 h, during low low-frequency noise levels and when the moon is nearly full

DISCUSSION

Assessment of PAM system performance

The PAM system was operational 24/7 for a period totalling 75.58 d. The system was able to reconstruct 3D tracks of animal movements around the turbine, albeit with fewer hydrophones than desirable. This is the first time a deploy-and-monitor approach has been applied for marine mammals at a tidal energy site, and demonstrates that the concept is feasible for future environmental monitoring projects.

Of PAM-operational days, 91% had porpoise encounters and 13% had dolphin encounters. It was unexpected that no dolphin whistles were detected on the system, although the whistle detector was clearly triggered occasionally by noises from mechanical flaps and from hydraulic pumps. It is not currently possible to identify the dolphin species from the clicks detected.

Estimating localisation accuracy from real tracks was impossible here since there was no 'truth' data as to where the sounds were actually originating from, but the poor quality of the tracks observed, combined with simulation studies, indicate that for porpoises (which were only being detected on a maximum of 5 hydrophones) range estimation errors were high — in the 10s of metres (Fig. 6). Dolphin clicks were generally picked up on 7 hydrophones, which improved accuracy.

Small cetacean movements and behaviours in turbine vicinity

Acoustic encounters were localised, and a number of events contained sufficient information to reconstruct 3D tracks of animals moving around the turbine and turbine platform (Fig. 10 & Fig. S1 in Supplement 1). The animal tracks presented here were the best examples from a PAM system whose performance was limited by the number of working hydrophones (Fig. 6). There is evidence of porpoises and dolphins coming close to the turbine when it was stationary (Figs. 10 & S1), and 1 example of a porpoise only 15 m from the turbine when it was operational and rotating. The right-angle turn that a porpoise made while approaching a non-rotating turbine (Fig. 10) indicates that the porpoise likely detected the turbine with its biosonar and responded accordingly by modifying its course so that it was heading away from the turbine. The porpoise, however, would have been capable of detecting the turbine with its biosonar from a farther distance, and this approach perhaps reflects investigatory but cautious behaviour.

The recording of a dolphin buzz at very close range (<5 m) to the turbine suggests that the dolphin could have been actively inspecting the DeltaStream structure. While it is possible that the dolphin was instead buzzing on a prey item near the turbine base (as it is possible that turbines could act as fish aggregating devices, Wilson et al. 2007), the hypothesis of dolphin investigatory behaviour is more likely given that no other buzzes were recorded during any of the 246 other acoustic porpoise or dolphin encounters. An absence of whistle recordings during any of the 11 detected dolphin encounters is also interesting. Predator presence has been correlated with reduced whistle rate in other toothed whales (Aguilar de Soto et al. 2012), and the absence of whistles recorded here could possibly indicate that the dolphins were modifying their acoustic behaviour in response to a perceived potential threat. Indeed, noise disturbance has been shown to modify the acoustic behaviour of toothed whales (e.g. Pirotta et al. 2014).

These close encounters, both when the rotor of the turbine was and was not rotating, have implications for collision risk. Our data suggest that porpoises and dolphins were able to detect the turbine both actively, via their echolocation clicks, and likely passively as well from the loud clangs. An important finding of this study is that animals approached the (rotating) turbine despite this. These few examples show that porpoises and dolphins were able to navigate around the device.

The probability of being able to localise a click reduced by 50% at a range of 20 m from the centre of the turbine base (Fig. 7), compared to a range of 1 m. This range is considerably less than has been achieved using other systems (e.g. Macaulay et al. 2017), but is expected given both noise issues limiting detection distance, and the fact that only 5 of 12 hydrophones were working for porpoises. Simulations showed that localisation accuracy would have been considerably improved had all 12 hydrophones been fully operational (Fig. 6). The fact that some tracking examples shown (Fig. 11) are at a range >20 m indicates that clicks in these click trains were likely more on-axis and/or louder, and also highlights the bias of the PAM system in picking up clicks from animals which were heading towards the array.

As the turbine was only rotating for a short portion of its deployment, turbine rotation was dropped as an explanatory covariate in the GAM-GEE model, and we could therefore not explain the presence of porpoises as a function of turbine rotation. As a result, the model could not show evidence for or against turbine rotation affecting the number of small cetaceans passing close to the turbine structure. Future projects where the turbine is rotating for longer will help to develop models of how turbine rotation impacts marine mammal presence and movement.

Patterns in acoustic detections in relation to environmental variables

It is likely that detection probability for harbour porpoises remained nearly constant throughout the tidal cycle due to high levels of electrical noise in the system, and this was confirmed by the model which did not retain high-frequency noise as an explanatory variable (Fig. 11). However, if the electrical noise had been absent, it is likely that there would have been a more significant increase in noise levels with tidal flow, and the analysis of future deployments must take changes in detectability due to noise into account. As a result of this, we have updated the PAMGuard click detector module so that it outputs click detection thresholds which are updated every few seconds according to background noise levels.

The explanatory covariate with the most weight was the tidal state (Fig. 11). This model indicated that porpoise detections were higher during the ebbing tide than during the flooding tide, and lower at peak flow. Fewer acoustic detections of porpoises and dolphins during periods of higher tidal flow (Fig. 8) therefore does genuinely indicate that fewer animals are present when the current is flowing. The fact that there were more detections at lower flow rates agrees with previously collected visual observation data at Ramsey Sound (Pierpoint 2008), suggesting that porpoises tend to be in the southern end of Ramsey Sound during the strongest part of the flow. Additionally, Barradell et al. (2013) observed porpoises transiting through the northern part of Ramsey Sound during slack tide (high and low water), where the turbine is located, and were observed foraging during the ebb tide in southern Ramsey Sound.

Numbers of acoustic detections were high compared to numbers of sightings, in part due to the much greater acoustic effort, but also due to the fact that most encounters occurred at night. Leaper et al. (2010) quantified range errors in the visual observation of marine mammals, and found high CVs for 7×50 binoculars (0.19–0.33) and naked eye (0.39) range estimates. With such high inaccuracy, it is technically possible that the distantly sighted porpoises are the same porpoises which are acoustically detected. These points emphasize the value of using PAM over visual surveys to assess environmental impacts of marine renewables.

More porpoise detections occurred at night than in the day (Fig. 11). Previous studies have shown that porpoise acoustic detection functions vary as a function of daylight (Koblitz et al. 2014) but when we recalculated the localisation probability function for acoustic encounters which occurred during daylight and during darkness, this pattern did not change, with both localisation probability functions similar to that shown in Fig. 7. Several studies using PAM have observed diel patterns in echolocation behaviour of porpoises at other tidal rapid sites (e.g. Haarr et al. 2009, Booth et al. 2011, Wood et al. 2013), and have suggested that it is likely related to the diel activity of their prey (Schaffeld et al. 2016). Additionally, diel variations in click activity have also been observed from recordings of some tagged porpoises (Linnenschmidt et al. 2013).

Low-frequency noise levels (0.7–1.4 kHz) were also significant in explaining porpoise presence (Fig. 11, Table 3). Porpoises could have avoided coming too close to the turbine during these noisier times. Note that low-frequency noise below the click detection band would not have interfered with detection performance, but the mechanical turbine sounds (clangs) possibly alerted animals in the vicinity as to the presence of the turbine, thereby aiding the animal's ability to detect and avoid the device without active detection (echolocation).

Note that these described patterns in porpoise presence may be under a seasonal bias (e.g. Cox et al. 2017), as data which fed into this model were collected during winter months (December to March), and may not be applicable to the rest of the year. The observed non-uniform patterns of porpoise occurrence around the tidal turbine are relevant for collision risk, especially since many collision risk models assume porpoises have a uniform distribution across the tidal cycle (Scottish Natural Heritage 2016). In this case in Ramsey Sound, since tidal pattern was a large predictor of porpoise presence, with encounters being highest during periods of lower flow, collision risk may be lower than predicted in collision risk assessments.

The site-specific and spatiotemporally variable distributions of porpoises in energetic tidal areas (Gordon et al. 2011, Benjamins et al. 2017), across tidal state, emphasizes the value of understanding occupancy patterns when conducting risk assessments (Scott et al. 2014, Waggitt et al. 2017a). For example, Macaulay et al. (2015) showed varying porpoise behaviours at 3 different tidal rapid sites in Scotland, with regard to both depth distribution and swim direction relative to the current. Differences in fine-scale porpoise distributions could reflect fine-scale habitat preferences in either porpoises or their prey (Embling et al. 2010). Other data suggest that variability in porpoise spatiotemporal distribution is related to tidal features characteristic of regions of hydrographic complexity, such as eddies, rips, upwellings and drop-offs, which could concentrate prey and create predictable foraging opportunities for porpoises (Pierpoint 2008, Booth et al. 2013, Wilson et al. 2013, Jones et al. 2014, Benjamins et al. 2015). Indeed, prey distributions are tidally driven (Simard et al. 2002), and these tidal currents play a role in shaping predator–prey dynamics (Zamon 2003, Johnston et al. 2005, Waggitt et al. 2017b). Therefore, due to site-specific behaviours and patterns of porpoise occurrence at tidal rapid sites, there may be limits to how much our findings regarding porpoise presence as a function of tidal state can be generalised to other sites.

Concluding remarks

Recommendations

For future studies, we recommend that at least 8 hydrophones are used in order to provide metre-scale localisation accuracy in the immediate vicinity of the turbine. We also propose the deployment of an artificial sound source pinger, close to the PAM array, in order to empirically assess localisation accuracy. Additionally, more data collected by a system with more working hydrophones are needed to better understand close approaches of marine mammals to marine renewable devices, as well as reveal how many acoustic detections from farther away turn into close approaches.

Ideally, future environmental monitoring for marine mammals at marine renewable sites would include monitoring prior to the deployment of the device (Cox et al. 2017). Consideration needs to be given to the methodology of this, so as to allow for the measurement of comparable metrics. For example, data from a hydrophone array like that described here could not be compared to CPOD data (www.chelonia.co.uk) due to high levels of ambient noise in tidal channels oversaturating the CPOD detector and buffer (Wilson et al. 2013), and due to its fundamentally different classification algorithms (Sarnocinska et al. 2016).

Acoustic data were collected using the PAMGuard software, which was configured to automatically detect both echolocation clicks and dolphin whistles. Critical to our understanding of both the system performance and additional factors which might affect animal behaviour close to the turbine was the collection and analysis of additional ancillary data, in particular noise levels at various sea states. One of the most notable sounds which may have alerted animals to the presence of turbines was the clanging of metal flaps on the support structure. These were only identified by listening to available WAV files recorded during the systems commissioning phase and by discussing this with turbine engineers who helped to identify the sound source. Similarly, identification of the hydraulic pump noise would not have been easy without being able to listen to sections of data and discuss the sounds' likely origin with turbine engineers. Unfortunately, these sounds were not always registered by the automatic detectors, and insufficient data were stored to detect all occurrences of these sounds during analysis. Seven hydrophones sampling at 500 kHz generate approximately 570 GB of acoustic data every 24 h period (~17 TB mo^{-1} of operation), so storing all audio data for a long deployment would be technically challenging and expensive. However, we strongly recommend storing a sufficient amount of raw audio data for PAM performance to be adequately assessed in different monitoring conditions. This would also allow for the identification of unexpected sounds, which may not have been picked up by automatic detectors. Future deployments should carefully consider how much raw audio data can be stored for additional offline analysis. Future projects should also ensure that appropriate measurements of parameters affecting system performance, such as noise levels in the detection band (now included as an output to PAMGuard's click detection module), are continuously measured throughout the deployment to ensure that factors that might reduce system performance (e.g. high noise during periods of high flow) can be separated from measures of animal behaviour.

Conclusions

The PAM system at this DeltaStream deployment allowed for the monitoring of small cetacean movements, and demonstrated progress towards tracking them around an operational turbine. The limited number of working hydrophones severely impacted our ability to localise and track animals, and we presume that had all hydrophones been functional, then the tracking performance would have been significantly improved. A few examples demonstrated that porpoises and dolphins were able to detect the turbine and manoeuvre around it, but we stress that such behaviours cannot be generalised to other sites. Compared to previous projects which had shut-down mitigation in place (e.g. the SeaGen tidal turbine project in Strangford Lough; Savidge et al. 2014), this system allowed for a more realistic and sustainable approach to monitoring at future tidal energy sites. The concept of using clusters of hydrophones to detect, localise and track echolocating marine mammals is translatable to different turbine designs and could be scaled up to marine renewable arrays currently being proposed worldwide.

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