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JASA ARTICLE

Tidal flow masks acoustic detections of harbour porpoises (*Phocoena phocoena*): Implications for passive acoustic studies of cetaceans

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ABSTRACT:
Passive acoustics is widely used to detect vocalising cetaceans, yet in tidal environments, strong currents facilitate sediment transport, creating "flow noise" that may mask signals and bias detection ranges. Although detection ranges are known to vary with background noise, the magnitude and spatiotemporal scale of such variation in tidal environments remain poorly quantified. Flow noise may fluctuate within tidal cycles and across small spatial scales, with consequences for estimating cetacean occurrence. To examine this, we tested the effects of flow noise on harbour porpoise (*Phocoena phocoena*) echolocation click detection, from data collected from an array of moored recorders in a tidal stream environment. Flow noise overlapping with porpoise clicks varied by up to 29 dB in mean sound pressure levels within tidal cycles (~12 h). Differences between sites <500 m apart were also significant, and modelled relationships between porpoise occurrence and tidal flow speed changed when a fixed detection threshold was applied. These findings show that flow noise in tidal habitats is heterogeneous across space and time, which may bias estimates of cetacean occurrence and distribution. Accounting for flow noise is therefore essential in ecological studies and is particularly relevant in environmental assessments of tidal energy developments.
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I. INTRODUCTION

Passive acoustic monitoring (PAM) is a method commonly used to detect vocalising animals; however, the efficacy of PAM and the detection of vocalisations produced by the target species is dependent on ambient sound levels. When there is overlap between the frequency and timings of animal vocalisations and external noise, this may influence the detectability of the target animals by PAM receivers, known as acoustic masking and has consequences for estimating species occurrence and distribution. Masking may occur from human-induced noise (anthrophony: e.g., ship noise) and other biological (biophony: e.g., snapping shrimp) or non-biological (geophony: e.g., rainfall) sounds.[1]

In the marine environment, studies that have accounted for masking relating to PAM detections have largely focussed on transient industrial sounds such as those produced from shipping and seismic airguns, which tend to occupy the lower frequencies (0–1000 Hz).[2,3] However, consistent sources of geophony are widespread in the marine environment.[4–6] Energetic tidal currents combined with shallow bathymetry and mobile substrates may create a consistent source of flow-derived ambient sound at higher frequencies via sediment transport (from 10 to hundreds of kHz).[7,8] Tidal environments are typically associated with high-energy shelf systems and are widespread with ~12.8% of the world's coastlines (≤25 km offshore) experiencing maximum tidal currents ≥ 1 m s^{-1}.[9] Although continental shelf seas cover ~8% of the global ocean area, they account for 16% of global ocean primary production[10] and support much of the world's marine top predator populations and it is well established that tidal environments provide important habitats for high densities of marine predators.[11,12] Sediment flow sounds overlap in frequencies with cetacean echolocation clicks, which creates potential issues for PAM, a common method for studying these vocal species, due to significant fluctuations in detection ranges or dynamic acoustic masking over tidal cycles (~12 h for semidiurnal tides). We hereafter refer to this as flow noise, but highlight the distinction between sediment flow as described in this paper and "self-noise" created by tidal currents causing turbulence around fixed hydrophones, which tends to occupy frequency ranges of 100–200 Hz.[13] Further, localised tidally-driven hydrodynamic features may result in heterogeneity of flow noise and thus detection ranges over very small spatial scales, impacting comparative studies of cetacean detections between study areas or even within PAM arrays.

The harbour porpoise (*Phocoena phocoena*) is a cetacean species that is commonly studied using PAM due to

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the production of distinct high frequency click trains.[14] Harbour porpoise clicks may be particularly susceptible to acoustic masking in high-flow environments as these overlap in frequencies and are narrow bandwidth in nature,[15,16] resulting in lower received levels of off-axis clicks on PAM instruments and a low signal-to-noise-ratio (SNR). Previous acoustic studies have suggested that porpoise distribution varies on micro-scales (minutes and 10s–100s of metres), which may be linked to foraging behaviour or reducing energy expenditure;[17,18] however, heterogeneous flow noise could result in misrepresented patterns in porpoise occurrence due to fluctuating detection ranges in space and time.

With marine industrial developments increasing in number and extent, porpoises, which exhibit a largely coastal distribution, are subject to various anthropogenic impacts.[19–21] Tidal stream energy is an emerging industry that focuses on areas with shallow waters and consistently strong current flows to power underwater turbines, predicted to contribute an equivalent of 11% of the UK's current energy demand.[22] Importantly, porpoises also commonly associate with high-flow environments, resulting in higher densities of animals in these regions.[12] PAM has been used to collect data on porpoise occurrence at tidal energy developments to investigate and quantify interactions with tidal turbines,[23,24] but flow noise in tidal environments has been found to vary by up to 20 dB within tidal cycles.[7,25] Failing to account for flow noise in PAM studies of tidal environments may bias estimates of porpoise encounter probability and spatiotemporal distributions. This may be particularly important in environmental assessments of the impacts of tidal energy developments.

Despite the potential significance of prominent and dynamic acoustic masking of cetacean vocalisations due to flow noise, to our knowledge, there are no published studies that have explored or quantified flow noise and its effects on assessments of cetacean occurrence and distribution.

The objective of this study was thus to investigate patterns of flow noise at small spatiotemporal scales relevant to known porpoise distribution variability.[17,26,27] Specifically, we assessed noise levels in relation to harbour porpoise click detections and distribution, using fixed detection thresholds applied to an array of moored PAM data. These were compared with untreated data using generalised estimating equations (GEE), a statistical approach commonly applied to assessments of cetacean occurrence and distribution,[17,28] to quantify the potential effects of acoustic masking on predictions of spatiotemporal occurrence.

II. MATERIALS AND METHODS

Using a small-scale array of seven moored acoustic recorders, porpoise click data were collected at all sites and compared to tidal flow speeds. Fixed detection thresholds were implemented for each site, where data were removed from low amplitude clicks and periods of high noise to reduce biases in detection and thus sampling area. Porpoise probability was then modelled relative to a single covariate, flow speed, for both original and fixed threshold data. The objective of this exercise was to compare models to test and account for the effect of flow noise on predicted porpoise distributions.

A. Study site

The study site is located off Holy Island, Isle of Anglesey (53° 18′N, 4° 42′W), within a consented tidal-stream energy lease area and in the North Anglesey Marine Special Area of Conservation (SAC), where harbour porpoises are a primary feature (https://sac.jncc.gov.uk/species/S1351/). Mean water depth is approximately 38 m, and the area is subject to semi-diurnal tides with mean and peak simulated velocities for this area of 1.6 and 3.7 ms^{-1}, respectively. Mean neap and spring peak velocities range from 1.7 to 3.1 ms^{-1}, respectively.[29] The seabed is composed of a mix of stony reef, bedrock, and mobile sediment.[30]

An array of seven acoustic recorders was moored on the seabed 500–760 m apart to investigate fine-scale occurrence and distribution (Fig. 1), in an area previously shown to host high densities of porpoises.[31] Specific mooring locations were selected where bathymetry was relatively uniform and rocky, avoiding areas of mobile sand visualised using existing multi-beam data.[30]

B. Data collection

Data were collected using SoundTrap 300 HF (Ocean Instruments, Warkworth, New Zealand), self-contained underwater acoustic recorders each with a built-in hydrophone with a working frequency range of 20 Hz–150 kHz ±3 dB. SoundTraps recorded WAV data continuously at a 48 kHz sampling rate and simultaneously ran an in-built high-frequency (HF) click detector, which was triggered when ambient sound levels exceeded 12 dB. For each trigger, sound clips comprising 750 μs before and after the event were retained as ".DWV" files sampled at 576 kHz.[32] In combination with an external battery pack, this allowed a longer data collection period of HF signals, required to detect porpoises. Each SoundTrap and battery pack was moored to a VR2AR acoustic release (Innovasea, Boston, MA) and Acoustic Release Rope Canister (ARC) (RS Aqua, Portsmouth, UK), enabling recovery of all mooring parts. Instruments were anchored to a 75 kg chain clump and suspended using a submerged buoy, approximately 3 m above the seabed.

Seven SoundTrap moorings were deployed between 24th July and 20th August 2018 at depths ranging between 35 and 39 m (Fig. 1). Since continuous recordings had a relatively limited bandwidth, a short deployment prior, on 18th and 19th July 2018 was conducted using the same instruments at each of the same locations recording at a sampling rate of 576 kHz, to record ambient sound at full bandwidth and "sense check" HF click detector flow noise estimates for a period of ∼24 h prior to the main period of data collection.

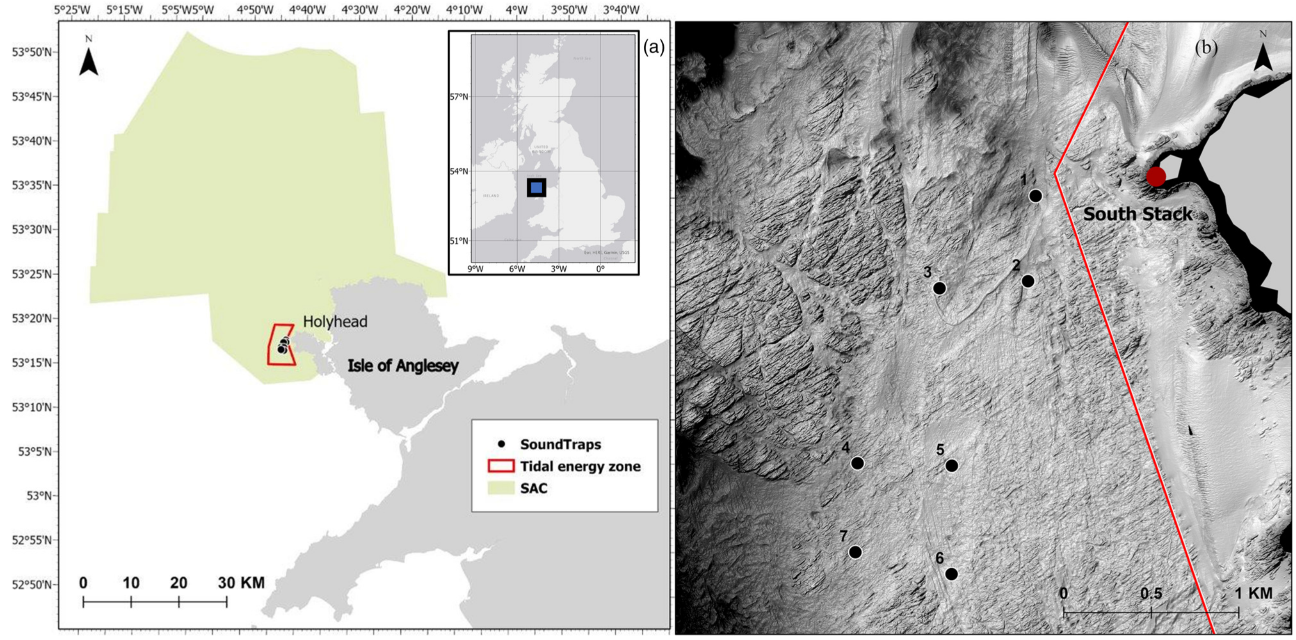

FIG. 1. (a) The PAM array was situated within the Morlais tidal energy zone and North Anglesey Marine SAC, off West Anglesey in the coastal Irish Sea. (b) Locations of SoundTrap moorings.

C. Data processing

Data were downloaded and decompressed after recovery using the SoundTrap Host software (Ocean Instruments) and click detector data were imported using the "SoundTrap Tools" import module in PAMGuard software v2.02.07[33] and processed using the PAMGuard click detector set to a 10 dB SNR threshold. Since the SoundTrap click detector was configured to trigger at a relatively low threshold, files containing non-cetacean sounds (unclassified "clicks") were also retained; therefore, the default PAMGuard harbour porpoise click classifier was also configured to identify possible porpoise clicks, to aid manual verification of true positive click events.

1. Porpoise event labelling

Harbour porpoise echolocation click frequencies centre around 130 kHz with click rates ranging from <10 to 250 ms and mean source levels of 191 dB re 1 μPa peak-to-peak @ 1 m.[34–36] Click trains were visually screened and labelled as "events" by at least one trained analyst, with a minimum of seven clicks required to be retained as an event as per previous studies.[37,38] Data were summarised into 15 min windows where porpoise events were scored as 1 or 0 if they were either present (Porpoise Positive 15 min, PP15M) or absent, respectively.

2. Assessment of flow noise and implementation of detection thresholds

The PAMGuard click detector extracts all transient signals which exceed 10 dB above ambient sound; therefore, during high noise periods, such as HF tidally-driven sediment flow noise, the absolute detection threshold is higher than at periods of low ambient sound (i.e., porpoise clicks may be masked). This masking may therefore vary considerably throughout tidal cycles, resulting in variable detection ranges within and between sites, if these are subject to different noise conditions. To investigate this potential bias, a sound threshold was defined at each site to provide a uniform probability of detection over time.[24] The HF click detector, which was set to a conservative 12 dB threshold, produced regular "click" detections and was therefore a good representation of samples collected throughout the deployment period. Ambient sound was estimated using the first 100 samples from each detection's snippet of wideband sound to produce the median sound pressure level root-mean-squared ($L_{p,\mathrm{rms}}$ in dB re 1 μPa) per hour of click data, then modelled and interpolated to provide a single median value of "ambient sound" per 15 min of data. To validate this estimate of ambient sound, we compared the $L_{p,\mathrm{rms}}$ data with the median $L_{p,\mathrm{rms}}$ calculated every 15 min from the full bandwidth ambient sound recordings collected $\sim$24 h prior to the principal deployment. A Kruskal-Wallis test was used to test for significant differences in noise between sites, followed by pairwise comparisons using a Dunn's Test.

Porpoise click amplitudes were estimated from clicks identified by the PAMGuard porpoise click classifier using default settings. To remove false positives, only clicks that corresponded to a time window where porpoise clicks had been visually confirmed by the analyst were retained. $L_{p,\mathrm{rms}}$ (dB re 1 μPa) of each detected porpoise click was calculated.

Simulations of the effects of applying a range of detection thresholds between 50 and 130 dB re 1 μPa were conducted, where porpoise clicks with received levels below the thresholds were removed. Where 15 min windows had fewer than seven clicks remaining above the detection threshold, they were marked as porpoise absent. Median $L_{p,\mathrm{rms}}$ of

15 min time windows over each threshold were also removed. A single absolute detection threshold was selected for each site at the crossing point of these variables, allowing a compromise between the percentage of porpoise events and time windows retained in the analysis,[24] providing a uniform detection probability over time (supplementary material Fig. SM1).

3. Flow speed estimation

Estimates of flow speed and direction were predicted for the deployment dates at 15 min intervals using a validated 100×100 m TELEMAC-2D hydrodynamic model that was developed for the site.[29] Data were extracted at each SoundTrap location using BlueKenue v 3.3.4 software (National Research Council, Ottawa, Canada).

D. Statistical modelling of porpoise occurrence

Data before and after the application of the detection threshold were modelled using porpoise events (presence/absence) as the independent variable and flow speed (ms^{-1}) as the dependent variable, to investigate the influence of flow noise on detection and predicted porpoise distribution. Exploration of the data using R Statistics software[39] suggested that a polynomial term would need to be fitted to model both original and fixed threshold datasets. A binomial generalised linear model (GLM) with a quadratic function was applied, with SoundTrap site used as an interaction term. Autocorrelation function plots of residuals showed significant temporal autocorrelation. GEE allow residuals to be correlated using a specified correlation structure within user-defined blocks and assumes independence between blocks.[28] Data were grouped into 2 h blocks, based on visual assessment of the GLM residual autocorrelation plots and binomial GEE-GLMs using the same variable specification, with an AR1 correlation structure, were fitted within the "geepack" R library.[40]

III. RESULTS

A. Harbour porpoise detections

Daily porpoise detection rates were relatively high at all sites, with up to 59% of 15 min time windows in a day containing porpoise clicks (PP15M) and total detection rates for the deployment period ranging from 17.6% to 36.4% PP15M (see supplementary material figure SM-1).

B. Flow noise

Tidally induced flow noise was evident in the full bandwidth recordings, ranging from 20 Hz to > 150 kHz in bandwidth and 65–120 dB per 1μPa [Figs. 2(a) and 2(b)]. Noise estimated from click data showed that all sites exhibited flow-induced noise, with the difference in mean $L_{p,\mathrm{rms}}$ per flow speed bin ranging from 10.8 to 28.5 dB between low and high flows (sites 7 and 1, respectively) [Fig. 2(c)]. Median $L_{p,\mathrm{rms}}$ per 15 min also varied significantly between sites (Kruskal-Wallis, $x^2 = 4835.9$, df $= 6$, $p < 0.001$) with

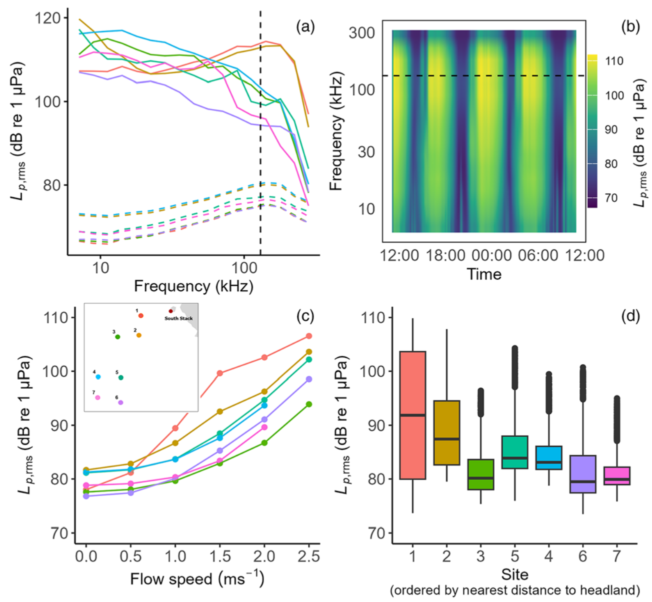

FIG. 2. (a) Spectra of minimum $L_{p,\mathrm{rms}}$ (dashed lines) and maximum (solid lines) $L_{p,\mathrm{rms}}$ (dB re 1 uPa) coloured by site. Black dashed line shows centre frequency of harbour porpoise clicks. (b) Spectrogram of 24 h of full bandwidth recordings at site 1, demonstrating flow noise at regular tidal intervals; (a) and (b) produced using fast Fourier transform (FFT) length = 1024 points, Hanning window and 50% overlap. (c) Mean ambient sound in each flow speed bin, estimated from median $L_{p,\mathrm{rms}}$ per 15 min (insert shows SoundTrap sites arranged by colour); (d) distribution of 15-min median $L_{p,\mathrm{rms}}$ values at each site, ordered by distance from South Stack headland.

Dunn's pairwise comparisons suggesting that all sites except 3 and 6, 3 and 7, and 6 and 7 were significantly different (see supplementary material table SM-I). $L_{p,\mathrm{rms}}$ and range decreased with increasing distance from a prominent headland [Fig. 2(d)].

C. Fixed detection threshold analysis

Noise variation across tidal cycles and between sites confirmed that the absolute detection ranges of the SoundTraps were unlikely to be uniform. Therefore, detection threshold simulations were conducted for each site. Between sites, selected fixed detection thresholds varied from 84.9 to 93.2 dB re 1μPa with percentages of total data removed after setting the threshold ranging from 38.3–64.5% (Table I). Percentages of porpoise events removed per speed bin were variable across sites, with a general pattern of more porpoise events with clicks lower than the fixed threshold in higher flow speed bins of 1.5–2 ms^{-1}. However, the percentage of porpoise events removed between low to high speeds was small, with a maximum of 18%; therefore, it was concluded that there was a relatively uniform distribution of porpoise events remaining across flow speeds (see supplementary material Fig. SM-2).

D. Effect of implementing detection thresholds on the probability of porpoise occurrence

Results of the model using the original (pre-threshold) data indicated that at all sites, flow speed had a highly significant effect on the probability of porpoise presence (Table II),

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TABLE I. Site-specific median sound pressure levels $L_{p,\mathrm{rms}}$ per 15 min estimated from click data, selected fixed $L_{p,\mathrm{rms}}$ thresholds (dB re 1 μPa) and percentage of data [porpoise events (click $L_{p,\mathrm{rms}}$ < threshold) and 15 min time windows (ambient sound $L_{p,\mathrm{rms}}$ > threshold)] removed.

Site	Median $L_{p,\mathrm{rms}}$ (dB re 1 uPa)	Threshold levels (dB re 1 uPa)	% Data removed
1	91.86	92.71	64.46
2	87.43	93.16	49.66
3	79.49	86.18	50.00
4	83.10	88.33	40.88
5	83.88	89.88	43.72
6	79.49	86.14	46.19
7	79.92	84.96	38.38

with peak probability ranging from 0.3 to 1 ms^{-1}, followed by a sharp decline with increasing flow speed at all sites. Peak probabilities shifted upward in the threshold model from 0.4 to 1.4 ms^{-1}, resulting in a 17%–75% increase in peak flow speeds compared to the original model (Fig. 3, see supplementary material, Fig. SM-3).

The model coefficients illustrate that for the threshold model linear predictors were 25%–76% larger across sites 2–7. Quadratic coefficients from the threshold model were 33%–56% smaller than the original coefficients. This illustrates that the distribution of predicted porpoise occurrence shifts towards increasing flow speeds with a less significant drop off in occurrence as speed increases (Table III; see full statistical model outputs in the supplementary material, Table SM-II).

IV. DISCUSSION

This study has shown that significant broadband noise associated with tidal and sediment flow masks harbour porpoise echolocation clicks from detection using PAM. Masking varied at small spatiotemporal scales, resulting in highly dynamic acoustic detection probabilities.

Tidal and sediment flow created broadband noise cycles every ~6 h that exceeded 150 kHz at all sites. Median $L_{p,\mathrm{rms}}$ ranges between low and high flow bins varied spatially from 10.8 dB at site 7 to 28.5 dB at site 1, similar to other tidal environments,[7,25,41] which is likely to result in high temporal variation in detection probability of porpoises within tidal cycles. Variation in $L_{p,\mathrm{rms}}$ levels between sites <500 m apart has important implications for comparisons of detections between multiple recorders. Previous studies have shown that variation in geological features changes acoustic detection probabilities at coarse scales of >300 km in humpback whales[42] and >8 km for porpoises.[43] However, to our knowledge, no study has previously investigated the spatial variation of HF call detection probability at such fine scales.

Palmer *et al.*[24] were the first to our knowledge to apply acoustic detection thresholds prior to assessing temporal patterns of harbour porpoises in a tidal environment. This current study represents a novel application of using detection thresholds to demonstrate the masking effect of geophony on patterns of porpoise occurrence, where spatial and temporal patterns in predicted porpoise occurrence consequently changed after implementing detection thresholds; spatial variation in porpoise occurrence using the original data was low, with all sites exhibiting peak probabilities ≤1 ms^{-1} followed by marked declines at higher flows. After setting a detection threshold, the peak probability of porpoise detection shifted to moderate flows at most sites, reaching up to 1.4 ms^{-1}. Further, the steep decline in porpoise probability with increasing speed was reduced after applying fixed detection thresholds, with quadratic coefficients 43.5% lower on average compared to original model outputs.

A. Additional factors influencing porpoise detection

Flow noise in our study was of a sufficiently high level that it is likely to have an overarching effect on detection range compared to other factors. Other variables that may influence porpoise detection include anthropogenic noise sources such as vessel or echosounder sound, but these are likely to be transient in this area and thus have a limited long-term masking effect on modelled porpoise occurrence. Broadband sounds recorded persistently during daylight hours, thought to be biophony from snapping crustaceans, were present in the data, but narrow band high frequency porpoise click trains could clearly be distinguished from these. Animal distance and orientation relative to the hydrophones are particularly relevant for porpoise detection due to the species' narrow click beam profiles and may be associated with tidal flow speed and direction.[44]

Porpoises may vary their echolocation behaviour in response to noise conditions; where studies have shown that animals reduce click rates when exposed to anthropogenic noise,[45] while geophony has been shown to reduce click source levels of porpoises.[46] Further, some odontocetes have been documented to use the "Lombard effect,"[47] an increase in vocal amplitude in response to high ambient

TABLE II. Wald's test results of GEE-GLMs for original and fixed detection threshold data.

Original				Threshold			
Parameter	df	x^2	P	Parameter	df	x^2	P
Flow speed	1	329	<0.001	Flow speed	1	0.6	0.46
Flow speed^2	1	157	<0.001	Flow speed^2	1	54.9	<0.001
Site	6	130	<0.001	Site	6	68.4	<0.001
Flow speed^2: Site	6	196	<0.001	Flow speed^2: Site	6	60.4	<0.001

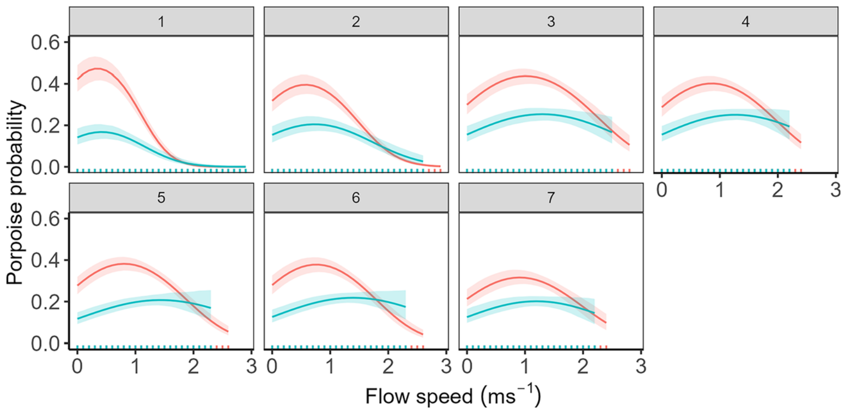

FIG. 3. GEE-GLM prediction plots of harbour porpoise occurrence in response to flow speed using original data (pink) and after the application of fixed detection thresholds (blue).

sound,[48,49] which has the potential to compensate for the masking of clicks to a degree.[50] However, this has not yet been documented for porpoises and further study is required to understand porpoise vocal behaviour in these environments and to quantify these effects on detection probability.

B. Other geophony and masking studies

It is well established in the literature that geophony is a significant contributor to ecosystem soundscapes, such as rainfall, wind and river flow.[1,51] Acoustic studies of tidal flows in marine environments, however, have focused on soundscape characterisation.[7,52] Further, most soundscape assessments record lower frequency sounds; therefore, acoustic studies of taxa that occupy high frequency niches are likely to be under-represented. This study shows that flow noise has the potential to mask high frequency specialist species, including most odontocetes, which is relevant for PAM studies investigating animal occurrence and distribution, comparisons between regions and multi-taxa soundscapes.

C. Limitations

This study sought to standardise relative, rather than absolute, detection conditions by removing site-specific data from periods of high noise and associated porpoise detections from those periods where the absolute detection threshold was likely to be very small. This resulted in fixed detection thresholds for each recording station; however, sites were largely exposed to the same tidal patterns, even if the absolute flow speeds and noise differed, with threshold variation being relatively low, between 85.0 and 93.2 dB per 1 μPa. Therefore, it was assumed that fixed detection thresholds were representative across sites. The study was also limited to estimating noise from the click trigger data collected by the SoundTrap click detector. We made the assumption that the click data sampled immediately prior to the presumed click was representative of true ambient sound conditions, which was validated by comparing 24 – 48 h of full bandwidth recordings (0–150 kHz) collected prior to the deployment. This method significantly extended the duration of data collected.

Data loss due to applying detection thresholds ranged between 38.3 and 64.5%. More advanced *post hoc* methods that involve modelling the probability of detection relative to SNR may be an option and would aid in reducing data loss.[53] Field solutions to reduce flow noise may include the use of drifting acoustic recorders instead of moored receivers,[54,55] but they are unlikely to collect data over long time scales and sampling locations may be biased by tidal current properties. Hydrodynamic flow shields covering hydrophones on fixed moorings may help to reduce flow noise in static PAM studies.[56]

PAM inherently cannot distinguish whether the absence of clicks is a result of an absence of animals in the vicinity of receivers, animals being present but not vocalising, or if

TABLE III. GEE coefficients for original and threshold models. Delta indicates the difference between model coefficients with (±) indicating the increase/decrease in difference, respectively. The percentage increase/decrease is also reported.

	Linear coefficients				Quadratic coefficients			
Site	Original	Threshold	Delta	% increase	Original	Threshold	Delta	% decrease
1	1.186	0.951	−0.235	−24.75	−1.718	−1.137	−0.581	33.83
2	0.739	1.047	0.308	29.45	−1.036	−0.649	−0.387	37.37
3	0.650	1.056	0.406	38.44	−0.587	−0.367	−0.220	37.47
4	0.592	1.055	0.463	43.88	−0.688	−0.376	−0.312	45.38
5	0.542	0.728	0.186	25.58	−0.735	−0.332	−0.403	54.83
6	0.554	0.811	0.257	31.74	−0.781	−0.341	−0.440	56.32
7	0.190	0.804	0.614	76.36	−0.653	−0.398	−0.256	39.16

vocalisations are produced but masked. Ground truthing with visual observations was not available as part of this dataset, and this is acknowledged as a caveat.

D. Implications

Studies using acoustic methods have concluded that harbour porpoises may vary their distributions at micro-scales, where it is hypothesised that associations with hydrodynamic features that form at similar spatiotemporal scales are utilised to optimise foraging opportunities.[17,57] However, sound propagation can be complex in tidal regions, with our study showing highly dynamic flow noise at scales of hundreds of metres, presumably associated with fine scale hydrodynamic features. This may lead to the misidentification of spatial and temporal patterns of porpoise occurrence; it is not clear whether the reported variation in porpoise activity at very small spatial scales in previous PAM studies[17,58] is a true representation of animal distribution or is driven, in part, by acoustic masking. Visual and telemetry studies have also shown that porpoises vary their distributions at fine scales[26,27,59] but further study into how geophonic sounds affect PAM detection and porpoise vocal behaviour is required. This current study has shown that flow noise changes both temporal and spatial patterns in porpoise occurrence, which has implications for ecological studies.

PAM is also being increasingly used in applied studies to investigate anthropogenic impacts, including tidal energy developments[23,24,60] and may be used in Environmental Impact Assessments (EIA) and Marine Licence monitoring to inform consenting and regulatory decisions. Spatiotemporal distribution studies can be used to estimate animal encounter probabilities, relative to tidal turbine location and operational speeds, to inform collision risk with turbine rotors.[60,61] Due to the acute and direct impact on levels of additional mortality, evidence relating to collision risk is currently a high priority for consenting and licencing relating to marine top predators. Further, determining the spatial scales at which animals are distributed and how flow noise differs between sites is critical for effective survey design, including the number and placement of PAM recorders, which will influence estimates of encounter rates, collision risk and other assessments of impacts such as displacement effects.

V. CONCLUSIONS

Tidally-driven flow noise overlaps with click bandwidths of many species of odontocete and results in highly dynamic acoustic detection ranges over fine spatial and temporal scales. PAM studies in coastal, tidal environments should therefore incorporate noise assessments to avoid bias, for effective studies and management of cetaceans in coastal waters.

SUPPLEMENTARY MATERIAL

See the supplementary material for supporting figures, tables, and additional analytical results.

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AUTHOR DECLARATIONS
Conflict of Interest

The authors have no conflicts to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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