Strategic Environmental Assessment of Wave Energy Technologies

SEA Wave

Report on quantifying ambient soundscapes at ocean energy technology developments

December 2021

Task 4.4 Ambient soundscapes

Deliverable 4.4. Report on quantifying ambient soundscapes at ocean energy technology developments

Contents

Disclaimer

1. INTRODUCTION

Sounds of human origin in aquatic environments originate from a range of activities including commercial shipping, geophysics, military activity, fisheries, civil engineering projects and leisure use [1]. This sound, termed anthropogenic noise, can also come from land and air-based activities that can be transmitted into aquatic habitats. Anthropogenic noise can be categorised into two forms: short duration, high energy impulsive noise; and more persistent noise that contributes to 'background' or ambient soundscape. Low frequency noise has increased at an average of 3dB/decade over last 50 years [2] and now pervades much of the marine environment in northeast Atlantic coastal waters [3].

Sound travels approximately four times faster in water than in air, with its propagation being dependent on its frequency and intensity, and the depth and density of water through which it travels. Low frequency sounds travel much further than high frequency sounds and under certain conditions, such as in deep water, can travel thousands of miles across ocean basins [4]. Aquatic environments are highly dynamic, as such sound can be reflected as a result of interaction with the substratum, the water/air interface or discontinuities in the water column, such as large gradients in temperature or salinity.

Marine organisms, from invertebrates through to marine mammals, react to anthropogenic noise in a range of ways, from changes in behaviour including changes in movement [5], vocalisation frequency [6], amplitude [7], through to changes in physiological function and in some cases physical damage to tissues [8], including temporary or permanent hearing threshold shifts, where it becomes more difficult to hear at particular frequencies [9].

Given sound travels much faster underwater than in air, and vision-based senses are limited, the dominant senses of aquatic organisms have evolved upon sound, gustation and electromagnetism and particle motion for some species [10]. Therefore, increases in underwater noise are likely to impact aquatic organisms and ecosystem services they provide.

Acoustic monitoring at offshore renewable energy sites has become common place as concern regards the effects of anthropogenic noise have increased. However, minimal acoustic data from this industry exist in the public domain, making multi-site comparisons challenging. This situation has arisen due to commercial sensitivity; but some notable exceptions exist, including Fred Olsen's BOLT2 at FabTest (Falmouth, UK) [11] and the ISWEC in the Mediterranean Sea (Pantelleria, Italy) [12]. Long-term (multi-year) acoustic characterisation has also occurred at Wave Hub (Offshore Cornwall, UK) in the Celtic Sea [13]. Alongside the aggregating / dispersing effect of human structures at sea, which can influence the distribution of fish [14], seabirds [15,16] and other predators [17], understanding the effects of anthropogenic noise remains a considerable knowledge gap for the offshore renewables industry, regulators and policymakers.

The European Marine Strategy Framework Directive (MSFD) and the UK Marine Strategy provide impetus to achieve Good Ecological Status of European coastal waters, and within these legal structures anthropogenic noise is considered through Descriptor 11. The existence of these legal requirements and the rapid planned expansion of offshore renewable energy across European waters highlights the need for offshore renewable energy developments to quantify and mitigate (where appropriate) their noise emissions to the marine environment. An essential step in this process is characterisation of the ambient soundscape of environments proposed for development of offshore renewable energy production.

The SEA Wave project (Task 3.4) used acoustic recording hardware to characterise the ambient soundscape at the Billia Croo wave energy site and at a comparative reference site across three years. Static hydrophones provided continuous acoustic data (weeks) on ambient noise variability during the boreal summer in each of the study years. Survey activities associated to Task 3.4 focused on ambient soundscape characterisation rather than deployments designed to capture wave energy device specific noise profiles (see [11,12], which can help in isolating mechanical and maintenance issues with renewables technology [18]. Acoustic recorders were active while Wello's Penguin Wave Energy Converter (WEC) was floating (2019) and after the device had sunk to the seabed (2020 & 2021). Technology suited to recording high-frequency animal communication (i.e. echolocation sounds), from dolphins and porpoises was also deployed (2021), gathering information on the presence of these species.

This report (Task 4.4) provides an overview of the ambient soundscape at both the wave energy site (Billia Croo) and at the comparative reference site. The report presents three established methods to assess marine soundscapes, including: i) Long-Term Spectral Averages (LTSA), ii) Percentile Sound Pressure Levels and iii) Third Octave Levels (TOL) assessment. TOL frequency bands (centred on 63-Hz and 125-Hz) are used in this report to describe anthropogenic noise contributions to the marine environment [19]. These bands are also used by the EU MSFD and by the UK Marine Strategy for monitoring anthropogenic noise. The three-month extension to the SEA Wave project (extended until December 2021) enabled additional data from field deployments in summer 2021 to be processed, analysed and considered in this report.

2. METHODS

2.1 Study area, survey design

Autonomous Multichannel broadband Acoustic Recorders (AMARs-G3; JASCO Applied Sciences; serial numbers 095 and 099; **Fig. 1**) were deployed with buoyant floatation collars at the Billia Croo wave energy test site and at northern reference site (**Fig. 2**). Deployments were made in August and September in 2019, 2020 and 2021, during annual monitoring campaigns performed by the Universities of Exeter and Plymouth. AMAR units were exchanged between sites each year to minimise the potential for recorder bias. AMARs recorded at 96 kHz frequency using a 5-min. on and 5-min. off duty cycle. Data were sampled using an onboard Analogue Digital Converter working at 16-bit resolution and operated GeoSpectrum M36_V35_900 hydrophones. Hydrophones were mounted within a protective cage, which was shrouded with a cloth hat to limit self-noise created by flowing water (e.g. during the ebb and flood tidal cycle; see **Fig. 1** yellow cloth shroud). AMAR hydrophones were calibrated during servicing prior to deployment. AMARs were accompanied by Xeos satellite tracking beacons tethered at the surface to aid monitoring of the units in case of accidental release or interference. AMARs in each year were deployed with the intention of creating a ~14 d deployment. AMARs were subsequently returned to shore for data upload and analysis. Data were downloaded from each AMARs using AMARLink proprietary software. Resulting data were *.wav Pulse Code Modulated (PCM) encoded acoustic files, one for each 5-min. recording cycle during the deployment period. Acoustic data recorded during the days of AMAR deployment and retrieval were eliminated from analysis to minimise potential influence of service vessels operating around the recorders related to other fieldwork activity.

Figure 1. *Soundscape recording equipment*. AMAR including buoyant floatation collar at sea surface upon deployment (left). GeoSpectrum hydrophone (top right) and CPOD (bottom right).

AMARs were co-deployed with CPODs in 2021 (Chelonia Ltd; serial no. 662 & 1144; **Fig. 1**). CPODs are acoustic recorders (cetacean click train detectors) whose operating frequencies are directed towards cetacean detection, these units record the time of putative cetacean detections and gather data on key aspects of the acoustic characteristics of these detections. These devices represent an alternative means of gathering acoustic data on biological organisms and are focused to higher frequency sounds made by small cetaceans, notably dolphins and porpoises. CPODs are designed for long-term deployments (months) and have been used widely in the offshore windfarm sector, they create lower volumes of data (in contrast to AMARs and other broadband recorders), hence allowing longer deployments between servicing events due to exhausted memory and power.
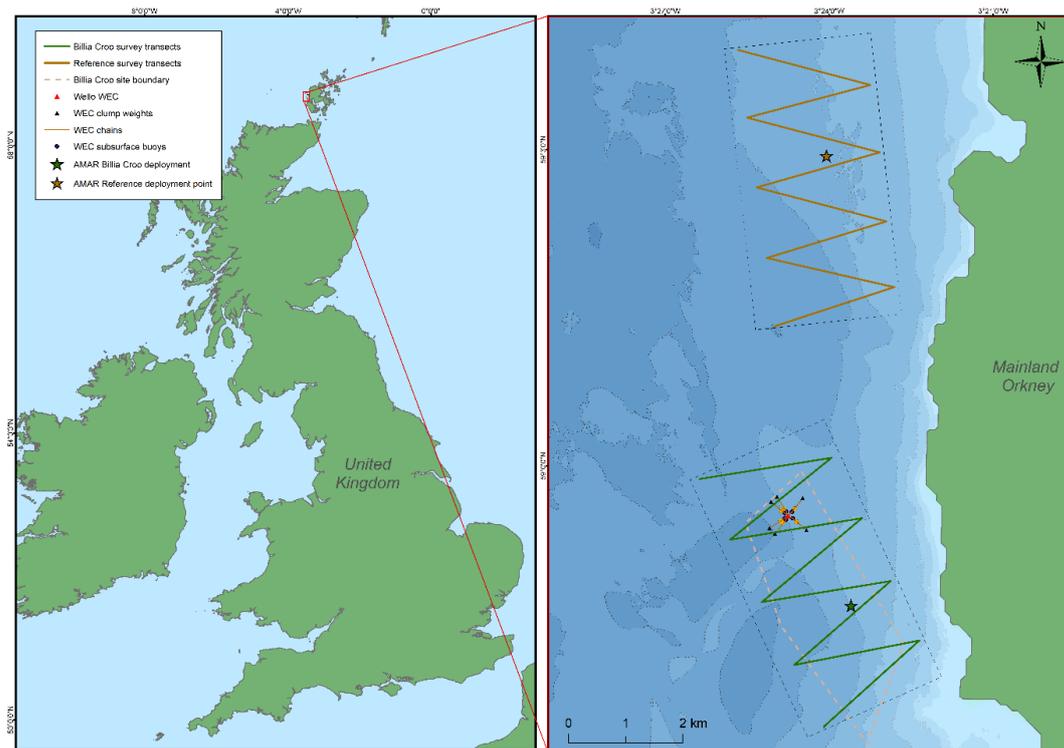
Figure 2. *Soundscape field deployments.* Billia Croo study area, showing annual boat survey transects (green and orange solid saw-tooth lines), WEC location (red filled triangle) and the Billia Croo test site boundary (broken dot-dot line). AMAR deployment locations (2019, 2020 and 2021; orange and green stars respectively for the North Reference site and Billia Croo). CPODs were co-deployed with AMARs (filled stars) in 2021.

2.2 Data processing

2.2.1 Visual evaluation using spectrograms

Each 5-min. acoustic recording was processed to a spectrogram image (process settings: 1024 samples, hamming window) using MATLAB's (The MathWorks; Massachusetts, version R2019a 9.6.0) spectrogram function. Visual evaluation of each spectrogram was conducted to identify noteworthy example sounds, noise events or specific recordings with potential contamination that might require manual removal from the acoustic time series.

2.2.2 Long-term Spectral Averages & Sound Pressure Level percentiles

AMAR acoustic data were processed using MANTA (Data Mining version R2020b.9.3.4; https://bitbucket.org/CLO-BRP/manta-wiki/wiki/Home). For each 5-min. duration recording, MANTA provided minute level summations of acoustic energy (dB re 1µPa) at a 1 Hz resolution up to 455 Hz and millidecade frequency bands above 455 Hz [20]. MANTA was populated with information on AMAR gain settings (dB; set at 6 dB), hydrophone characteristics and calibration data to ensure results from differing units could be robustly compared. Data outputs from MANTA were used to: i) construct Long-Term Spectral Average soundscapes (LTSAs) at each site for each year (i.e. two acoustic time series per annum for three years), and ii) create Sound Pressure Level (SPL) percentile plots revealing statistical distributions (5th, 10, 25th, 50th (median), 75th, 90th and 95th percentiles) for the equivalent soundscapes. R (version 4.0.3) scripts were developed to visualise the processed MANTA data using the ggplot2 package [21].

2.2.3 Third Octave Levels

Third Octave Level (TOL) frequency analysis is a standardised approach to summarise energy levels occurring within internationally agreed frequency ranges [22]. The acoustic frequency bands centred at 63 Hz (56 – 70 Hz) and 125 Hz (111 – 140 Hz) were used to investigate anthropogenic noise. To assess sound levels (dB re 1µPa) for each deployment within the 63-Hz and the 125-Hz bands, *.wav data resulting from each AMAR deployment were analysed using the PAMGuardBeta (version 2.01.05) Noise Band Monitor module. To eliminate artefacts of hydrophone pre-amp "warm-up" the first 10 seconds of each 5-min. recording were excluded from analysis. The mean dB value for each processed *.wav file was analysed using boxplots [23] created with the ggplot2 package in R (version 4.0.3) and RStudio (2021.09.1 Build 372).

2.2.4 Sounds of biological origin

PAMGuard. Acoustic data (*.wav files) from AMARs were analysed using PAMGuardBeta (version 2.01.05) Whistle and Moan detector. Detector parameters were set using a minimum frequency of 9000 Hz, a maximum frequency of 48000, a minimum length of 20 time slices [equivalent to 0.1 seconds], a minimum total size of 100 pixels and a maximum cross length of 5 times slices. The minimum frequency filter was purposely set high due to persistent anthropogenic noise (approx. 5 kHz frequency range) initially resulting in a high number of false positive detections, notably at the Billia Croo site. As a result, only higher frequency sounds (> 9000 Hz) were considered for this analysis, and low frequency sounds excluded. The daily number of hours with detections meeting the detector criteria were calculated for each deployment day where a full 24-hour sample was available (i.e. removing deployment and retrieval days) and visualized using the ggplot2 package in R (version 4.0.3) and RStudio (2021.09.1 Build 372). Temporally aggregating data in this way limits the potential for repeat detection over short timeframes (e.g. pseudo-replication). A one-hour summary interval was considered sufficient to create independence between detection episodes. Detection positive hours should not be inferred as cetacean abundance, but as cetacean presence / absence.

CPODs. Raw data gathered by CPODs require post-processing to determine the acoustic characteristics of putative small cetacean detections (e.g. duration of event, frequency minima, maxima and range, number of clicks per detection train etc.). Each detection train (i.e. a collection of validate clicks) is assigned a quality score (i.e. low, moderate or high) concerning is probability of originating from a cetacean source and a putative animal group (i.e. "dolphin" or "narrow-band high frequency cetacean – aka. porpoise"). Detections of trains was achieved using the CPOD.exe Kernow classifier. Post-processed data (i.e. a time series of cetacean click train detection events) was expressed as the number of detection positive 10-min. periods per one-half tidal periods (e.g. approx. 3 h duration).

2.2.5 Data availability

Given the size of the AMAR acoustic datasets created during the project (raw: 1.01 TB; post-processed 52GB) data could not reside on the SEA Wave web-based data server (MARENDATA portal; https://marendata.eu). Raw and post-processed data are available on request from the University of Exeter (Dr Matthew Witt; m.j.witt@exeter.ac.uk, or Dr Anthony Bicknell; a.bicknell@exeter.ac.uk).

3. RESULTS

3.2.1 Acoustic hardware deployments & data evaluation

Annual deployments of AMARs were undertaken in August and September 2019, 2020 and 2021 (**Table 1**). CPODs accompanied AMARs during deployments in 2021. Acoustic sampling activities using AMARs produced between 1,728 and 2,592 *.wav data files and 8,640 and 12,960 minutes of acoustic data per deployment (**Table 1**). All acoustic data were visually inspected using spectrograms (**Fig. 2**) and aural validation. Examples of distinctive noise events encountered at the sites, including chain and engine noise, were identified and checked during the quality control process of gathered acoustic data by the AMARs (**Fig. 2**).

Table 1. AMAR deployments. *Includes deployment of accompanying CPOD.

| Site	Year	Unit ID	Data start date	Data end date	Deployment duration (days)	Recording (minutes)	Files (n)	Gb (n)
Billia Croo	2019	AMAR099	22/08/2019	07/09/2019	18	12,960	2,592	212
	2020	AMAR095	14/08/2020	26/08/2020	14	10,080	2,016	165
	2021	AMAR095	21/08/2021	02/09/2021	14	10,080	2,016	165
North Reference	2019	AMAR095	26/08/2019	07/09/2019	14	10,808	2,016	165
	2020	AMAR099	16/08/2020	26/08/2020	12	8,640	1,728	142
	2021	AMAR099	21/08/2021	03/09/2021	14	10,080	2,016	165
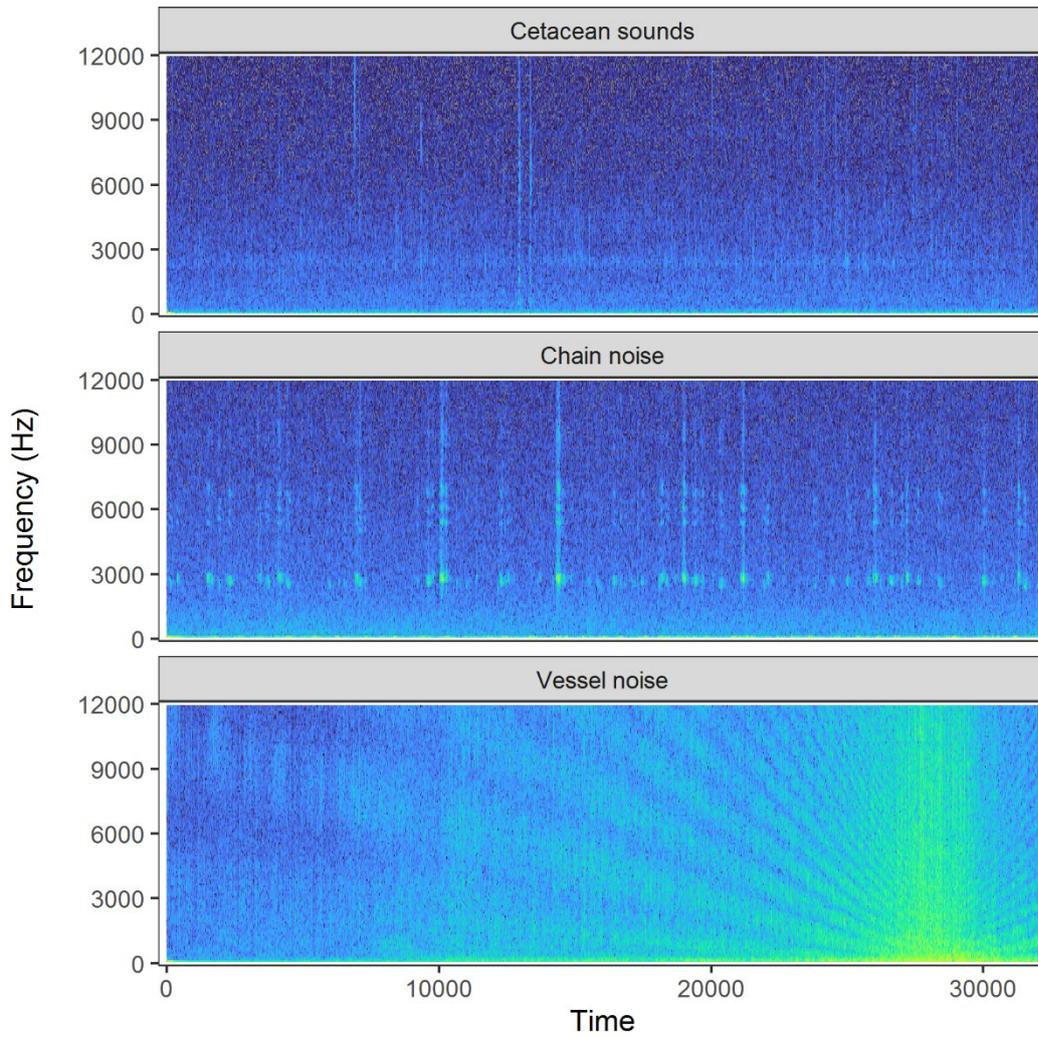
Figure 2. *Example 5-min. duration spectrograms for visual data validation.* (Top panel): High frequency cetacean sounds (i.e. whistles), (Mid panel): mid to higher-frequency chain noise, and (Lower panel): passing vessel noise.

3.2.2 Long-term Spectral Averages

Long-term Spectral Average (LTSA). LTSAs revealed soundscapes to be dynamic with distinctive acoustic signatures at both Billia Croo and the North Reference site in all years. The Billia Croo soundscape was more heterogenous with more regular low frequency noise events of high energy (dB), particularly in 2021 (between 8 and 12 days elapsed). The North Reference site experienced fewer loud noise events that rarely exceeded noise levels at Billia Croo across all sampled years (**Fig. 3**).
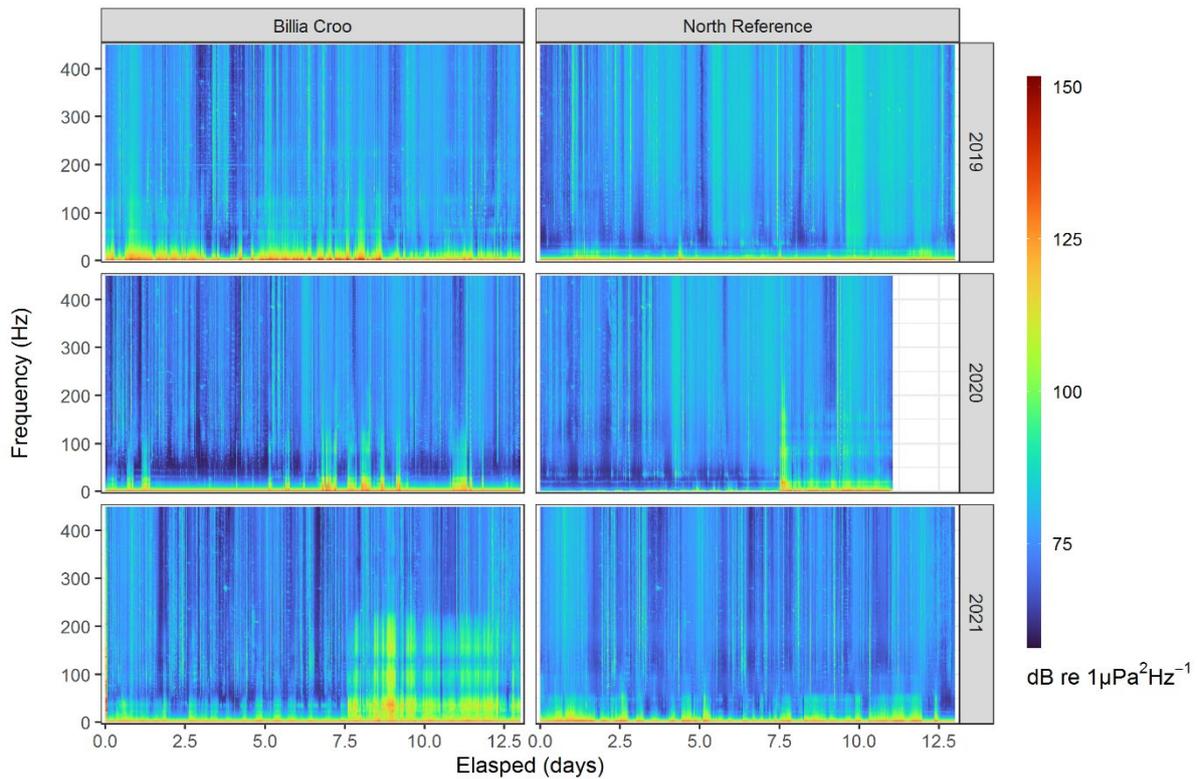

Figure 3. Long-term Spectral Averages. Data presented for Billia Croo (left column) and North Reference site (right column), by year (rows). Data expressed as elapsed days (x-axis) from commencement of first complete day at sea. Maximum frequency (y-axis) 450 Hz. Data grouped by site and year.

3.2.3 Sound Pressure Level percentiles

SPL percentile analysis revealed a heterogenous pattern of sound energy (1 to 15,000 Hz) at both sites (Billia Croo and North Reference) and among years within sites (**Fig. 4**). Billia Croo experienced a persistent energy signature at 4800-5000 Hz across all percentiles in all sampling years. This signal was absent from the North Reference site.
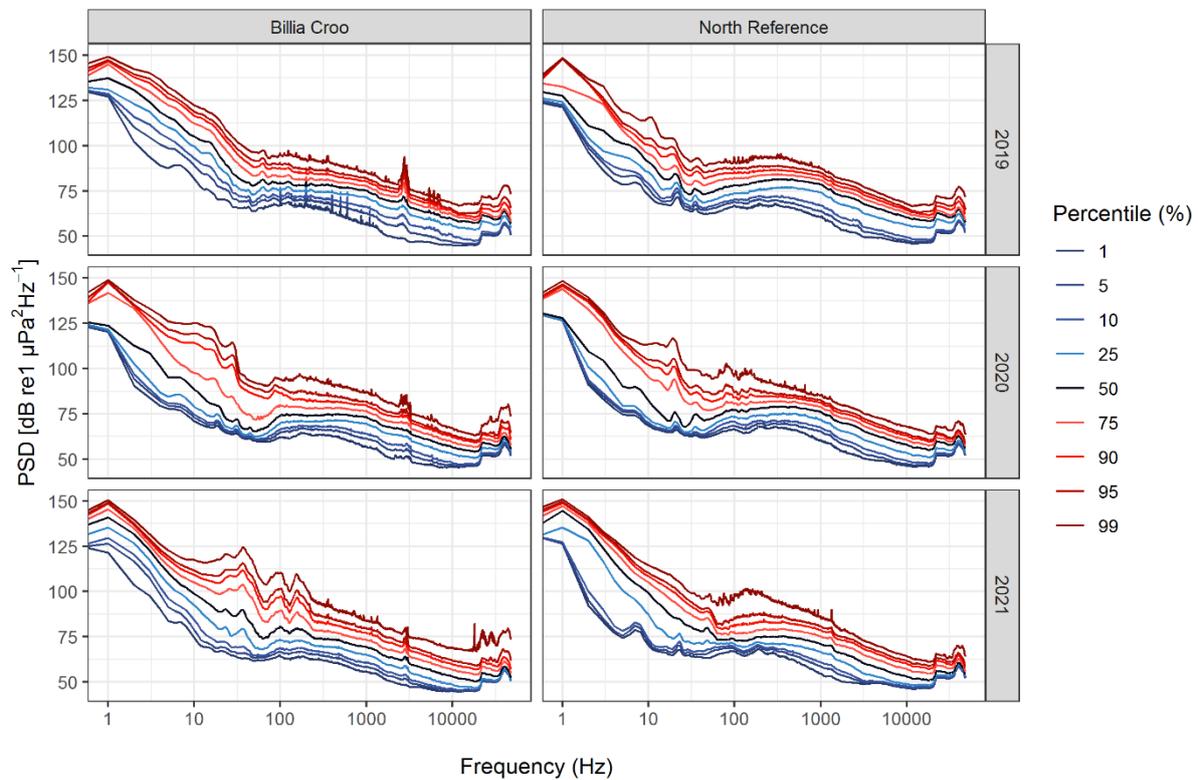

Figure 4. *Sound Pressure Levels (SPLs).* Sound Pressure Level percentile plots for the Billia Croo and North Reference sites across years. Data grouped by site and year.

Median and 90th percentile Sound Pressure Levels were broadly similar across years at both the Billia Croo and the North Reference sites (**Fig. 5**). For Billia Croo, 2020 appears to have been the quietest year at the site (1-100 Hz) during the three years of monitoring; this might reflect the reduce vessel traffic due to the safety concern represented by the Penguin WEC.
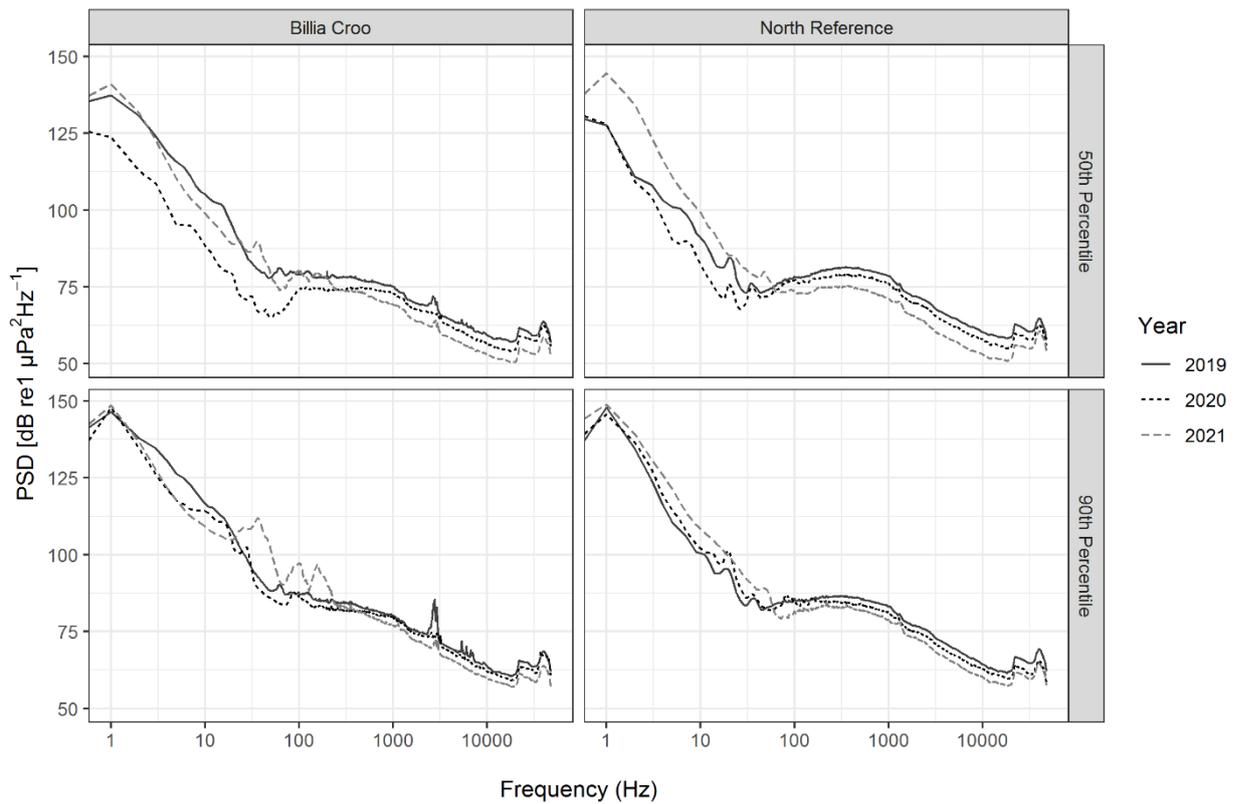
Figure 5. *50th (median) and 90th percentile Sound Pressure Levels (SPLs).* Selected SPLs for Billia Croo and the North Reference site. Data grouped by site and percentile class.

3.2.4 Third Octave Levels

Mean sound levels (dB re 1 µPa) at the North Reference site revealed limited variation across 2019, 2021 and 2021 for both the 63 and 125 Hz TOL indicator bands (**Fig. 6; Table 2**). Noise levels were more variable for the Billia Croo site, with noticeable reduction in energy in the 63-Hz band in 2020. In general, mean third octave levels were louder within the 125-Hz band (cf. 63-Hz band) for both sites across all years (**Fig. 6**).
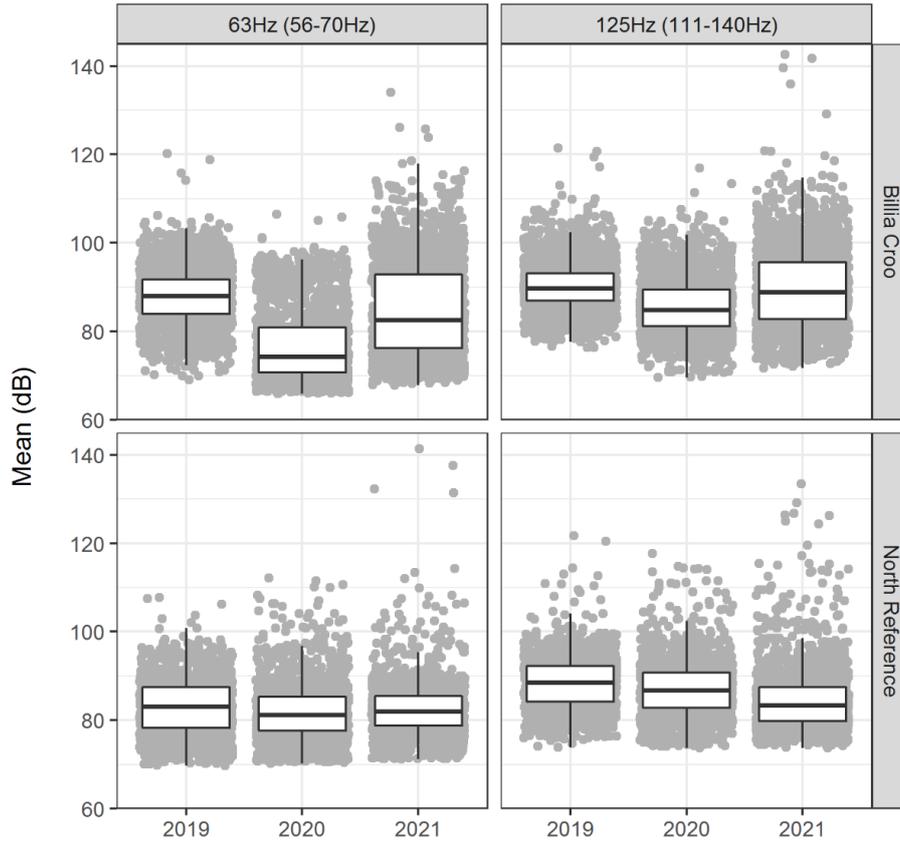
Figure 6. *Third Octave Levels (TOLs).* Box and whisker plots of mean third octave level values for the 63-Hz and 125-Hz bands EU-MSFD indicator bands of anthropogenic noise for deployment sites and years. Data grouped by TOL frequency band and site.

Table 2. *Third Octave Levels (TOLs).* Comparison of available TOL values gathered for SEA Wave with other sites.

	SEA Wave						Garrett *et al.*, 2016		Merchant *et al.*, 2016		
	Billia Croo			North Reference			Falmouth (Bolt Lifesaver)		Celtic Sea (Wave Hub)	N. North Sea	S. North Sea
TOL	2019	2020	2021	2019	2020	2021	2012	2013	2013-14	2013-14	2013
Mean											
63 Hz	-	-	-	-	-	-	90.0	88.1	-	-	-
125 Hz	-	-	-	-	-	-	94.7	93.3	-	-	-
Median											
63 Hz	87.9	74.3	82.6	83.1	81.2	81.9	-	-	82.0	90.5	94.7
125 Hz	89.8	84.8	88.8	88.5	86.7	83.3	-	-	83.3	93.6	86.0

3.2.4 Sounds of biological origin

PAMGuard. The PAMGuard *Whistle and Moan detector* indicated cetacean activity within the range of each of the AMAR devices (**Fig. 7**). Detections (cetacean positive hours per day) were higher at the Billia Croo site than the North Reference site in all years, with a peak of 16 detection positive hours recorded in 2020. The North Reference site experienced several days with no detection in 2019 (5 of 13 days) and intermittent zero detection days in 2020 and 2021.
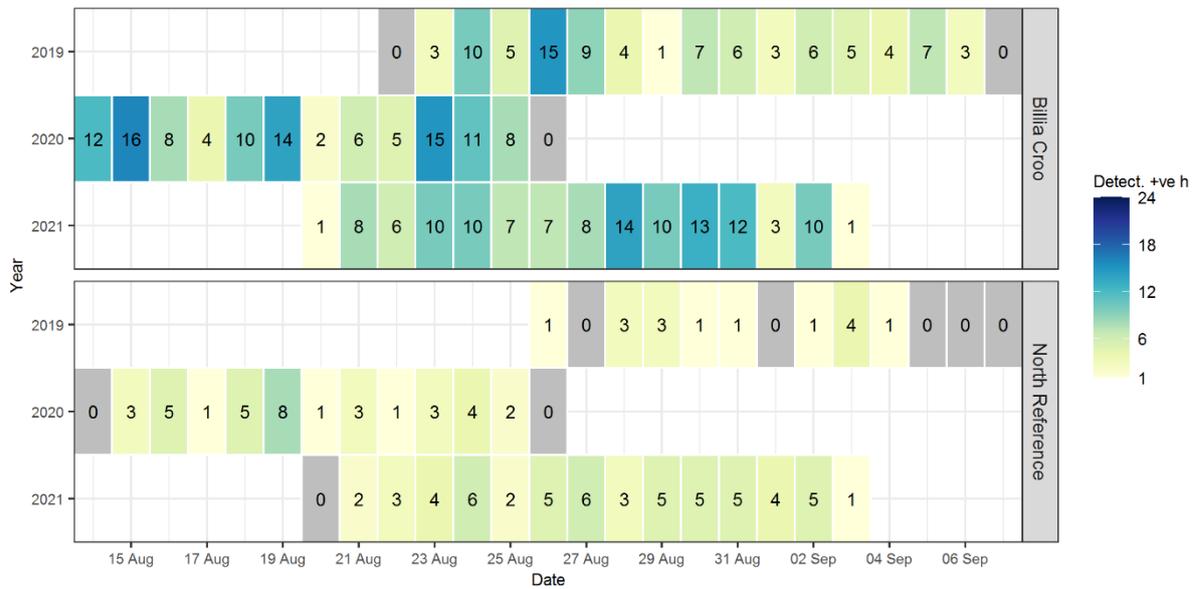

Figure 7. *Cetacean positive hours per day.* Daily number of hours with high frequency biological detections by deployment site and year. Period where no detections were made (grey). Arabic numbers denote number of hours per day cetacean sounds were detected.

CPODs. Cetacean click train detectors were simultaneously deployed with AMARs in 2021 at the Billia Croo and North Reference sites. Dolphin detection rates were greatest between the 25th and 28th of August at Billia Croo (*cf.* North Reference site). Given the overlapping acoustic frequencies of many small dolphin species found in the northeast Atlantic it is not possible to discriminate delphinid species using CPODs. Harbour porpoise click trains were detected on all sampling days at both sites (**Fig. 8**).
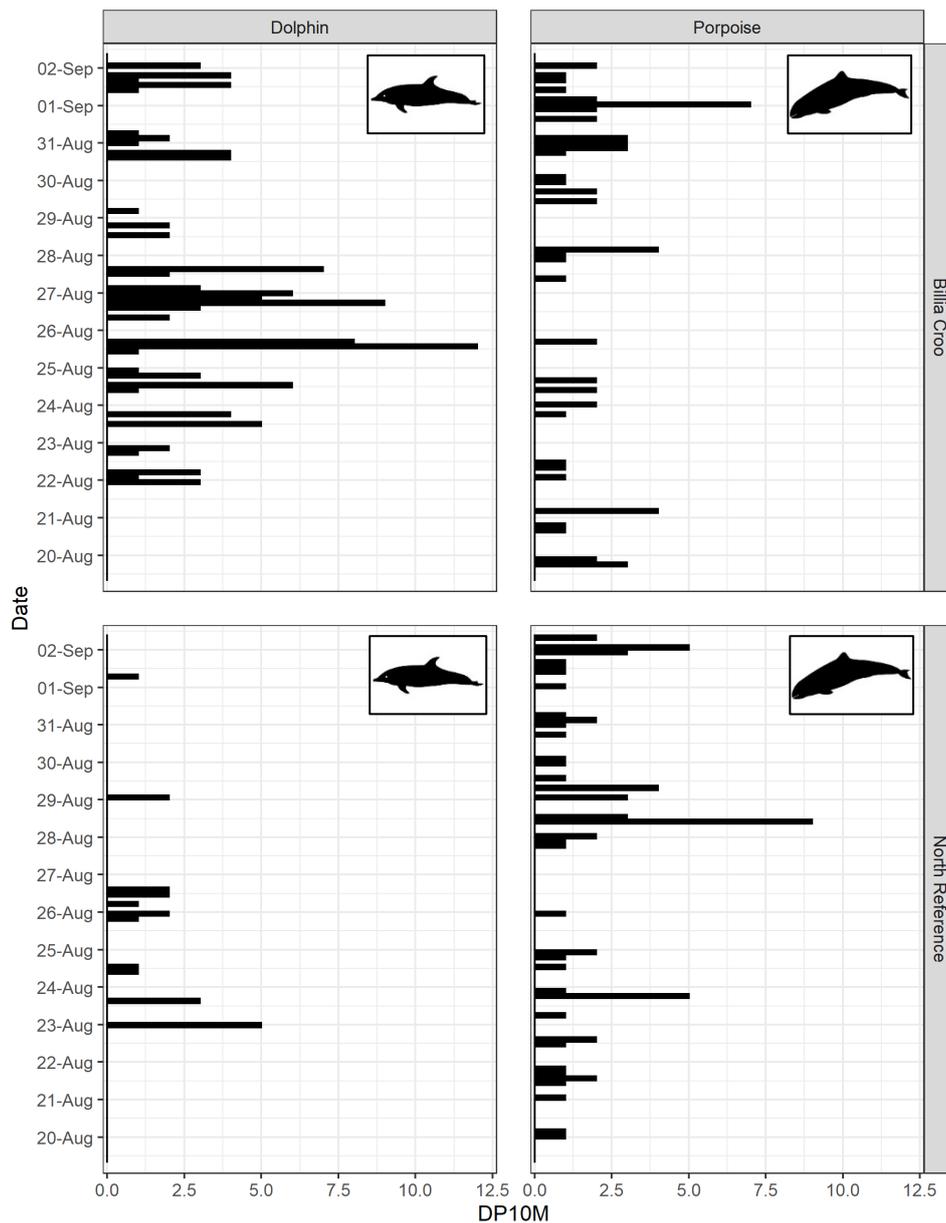

Figure 8. *Cetacean detection positive 10-min periods (DPM) at ~3-hour intervals during summer 2021 deployments.* Dolphins (left panels) and Narrow Band High Frequency (porpoise) (right panels). Data grouped by species and site.

4. DISCUSSION

This report provides a characterisation of the ambient sound field at the EMEC Billia Croo wave energy site during the summer of 2019, 2020 and 2021. This survey effort was to support the operation of planned multiple wave energy converters during the SEA Wave project. Systematic site characterisation is an important process prior to the development and operational of renewable energy sites to ensure a robust understanding exists of the host ambient soundscape. Noise contributions from renewable energy installations can then be appropriately contextualised, and where necessary, mitigated to ensure large scale civil engineering projects do not impinge on local ecosystem function. Mitigation may come through modification of existing WECs, or most likely subsequent version of these devices, to minimise noise producing features, which might arise from hull slap, mooring systems, or from on-board electrical or mechanical power take-off systems.

The SEA Wave project encountered several challenges during grant period, including the sinking of Wello's Penguin 1 soon after the project commenced. Other WEC project partners subsequently moved their technology to Portugal and Hawaii due to financial incentives or operational enhancements. As such, site level characterisation of the ambient soundscape at Billia Croo was limited in its ability to deliver the anticipated results for the project.

A variety of analytical approaches were used to provide a broad overview of the ambient soundscape, these included Long-term Spectral Averages (LTSAs), percentile distributions of calibrated Sound Pressure Levels and Third Octave Level (TOL) analysis for two commonly used anthropogenic noise indicator bands (63-Hz and 125-Hz). Passive acoustic monitoring for sounds of biological origin was also undertaken.

Long-term Spectral Averages (LTSA)
LTSA analysis can reveal dominant frequency bands experiencing high relative levels of acoustic energy (e.g. persistent or episodic noise) or episodic sound/noise events (e.g. tidal noise, increases in the ambient sound field from weather events, acoustic chorus from fish and other animals etc.). LTSA analysis in this report (Fig. 3) was restricted to the frequency range 0-450 Hz, hence the outputs broadly cover low frequencies, including anthropogenic noise, often associated to vessel activity. The approach is helpful for acoustic time series data that can represent many gigabytes of data, which are often challenging to communicate to non-technical audiences, and is particularly useful to visualise the ambient sound field at locations of interest [13]. However, conducting LTSA analysis is particularly demanding on computing time and hardware resources. LTSA analysis revealed the ambient soundscape of Billia Croo was influenced by episodic loud noise events (high dB) at low frequency and revealed heterogeneity in sound pressure levels, through time and frequencies. By comparison the soundscape at the North Reference site was more homogenous, revealing less variation through time, energy and frequency.

Sound Pressure Levels (SPLs)
Billia Croo experienced a persistent energy signature at 4800-5000 Hz across all percentile bands (i.e. 5th to 95th percentiles) among all sampling years (**Fig. 4**). This signal is, however, absent from the North Reference site. The source of this signal is unknown, but potentially related to electrical or mechanical infrastructure present at the Billia Croo site, or from highly regular vessel traffic at all hours of the day. Given the changing operational status of the single Penguin WEC at Billia Croo (i.e. 2019: floating, 2020 & 2020: device on the seabed) it seems unlikely the source is associated to the Penguin electrical infrastructure itself. Visual inspection

of spectrograms (with additional aural checking) of the Billia Croo acoustic dataset reveal intermittent chain noise, vessel events and cetacean activity, though none of these events appeared to comprehensively contribute to the signal occurring at 4800-5000 Hz. These types of acoustic events also occur at the North Reference site, but they also do not seem to substantially contribute a dominant signal between 4800-5000 Hz. AMAR units were exchanged between sites across years, so the signal cannot be attributed to a device-specific recording artefact.

Acoustic recordings were undertaken in each year of the SEA Wave project, but minimal operation and maintenance activity due to almost absent WECs, and further reduced activity due to safety concerns around the sunken Penguin WEC, meant the ambient soundscape revealed minimal variation. The median (50th percentile) sound pressure level at both locations was broadly similar across years (**Fig. 5**). However, sound pressure levels described by the 50th and 90th percentiles for frequencies ≤100 Hz were typically more variable among years than for frequencies >100 Hz. At the North Reference site, low frequency noise (≤100 Hz) was greatest in 2021 (**Fig. 5**).

Third Octave Level assessment
The Billia Croo and North Reference sites were broadly quieter (median TOL dB across both the 63-Hz and 125-Hz indicator bands; **Fig. 6**) than other European locations where extended acoustic time series have been created, including the southern and northern North Sea [13] (**Table 2**). This pattern is not unexpected given the relative sheltered nature of Billia Croo from widescale shipping activity [3]. The Wave Hub site in Falmouth, Cornwall [13,24], which is broadly similar in habitat, was quieter than either Billia Croo or the North Reference site. This site however has lacked grid connected WECs for its entire operational history. Whilst other studies used to contextualise the recordings at Billia Croo (**Table 2**) used differing survey regimes (i.e. total deployment length, sampling rates, device manufacturer), they provide a useful indicator of the relative low-frequency continuous sound levels (an indicator of anthropogenic shipping noise pollution) at the Billia Croo site.

Biological sounds
The results of the *Whistle and Moan detector* analysis (**Fig. 7**) should be treated with some caution. The minimum frequency used in the detector parameters (9000 Hz) is higher than the preferred minimum (i.e. ~1000 Hz) considered applicable to the whistles of dolphins (*Delphinidae spp.*) and as such the detector may underestimate the presence of larger cetaceans to which this method is appropriate. Complicating the interpretation of these results is the potential for false positive detections associated with chain noise events, potentially explaining the high number of detections at the Billia Croo site where chain noise is evident. It is the presence of this persistent chain noise that prevents the minimum frequency in the detector being set below 9000 Hz. However, chain noise may still contaminate the cetacean detection data. It was not feasible to completely remove all false positive detections associated with chain noise as further increasing the minimum detector boundary beyond 9000 Hz resulted in the detector lacking sensitivity and missing known cetacean sounds events identified during the visual and aural evaluation of the spectrograms.

Given the rather limited operational activity at Billia Croo during the SEA Wave project it is challenging to address potential issues of acoustic masking that may result from the operation of the Penguin WEC at the site. While the WEC was operational in 2019, fieldwork occurred during the boreal summer when wave activity is minimal and hence the WEC is least active. Characterisation of WEC-associated noise through a full range of operating conditions, in

context of the ambient soundscape, was not possible. This issue was further complicated by persistent noise between 4800-5000 kHz, the source of which cannot be established following discussions with EMEC. Nonetheless, this acoustic frequency is in the hearing range of many cetaceans and pinnipeds [1,25].

In 2021, the SEA Wave project deployed cetacean click-train detectors specifically focused on the detection of small dolphins and porpoises (**Fig. 8**), which broad-band sounds recorders cannot record without substantially reducing deployment duration due to rapid memory exhaustion when recording at very high frequencies (i.e. ≥300 kHz) needed for click train detection. The acoustic click frequencies of harbour porpoises are sufficiently different to delphinids that is possible to discriminate these species groups from acoustic data. Common dolphins (*Delphinus delphis*) and harbour porpoises (*Phocoena phocoena*) are ubiquitous marine mammals in the coastal seas of the northeast Atlantic and so their detection by CPODs at the Billia Croo site agrees with the general understanding of their distribution [26].

Conclusions

Acoustic recording equipment are best deployed for many months (>3 months), on multiple occasions, to provide long-term data that could reveal within and among seasonal variation in the soundscape. This has been achieved elsewhere [11–13,27], but requires regular maintenance and monitoring to ensure the persistence and operation of the recording devices. The resources to maintain such near-continuous monitoring were not available within SEA Wave, so monitoring was limited to short annual summer recording periods. The characterisation of the ambient acoustic environment for this period has however provided invaluable baseline data for future deployments of WECs at the EMEC Billia Croo test site to use for impact assessments. This report provides a range of analytical outputs helpful in contextualising the environment.

With long-term annual monitoring and the presence of operating WECs, further assessment of the local ambient soundscape will help to build an understanding of how wave energy infrastructure might influence marine ecosystems. The presented analyses in this report are not exhaustive and further analytical areas could include acoustic diversity indices and investigations in the acoustic chorus of fish [28]. Monitoring throughout all seasons will also be important since the community composition is likely to change throughout the year following migration/emigration of species. This type of continuous monitoring was not possible with the resources available within the SEA Wave project but represents an important avenue for future research, which will help in de-risking environmental aspects of wave energy sector prior to significant upscaling across European waters.

While the project suffered several considerable challenges, the acoustic data gathered within the project represents an essential dataset to EMEC and the wider industry and will be available for their use.

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