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Impacts of large-scale maintenance of a floating offshore wind farm on noise levels and harbour porpoise activity

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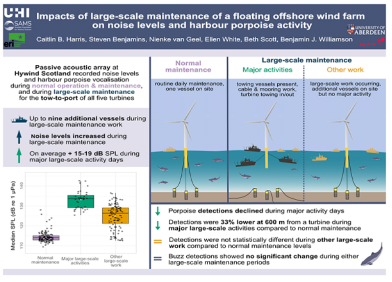
Abstract

For some floating offshore wind designs, turbines can be disconnected and towed to port for major component replacement, but the ecological effects of these operations remain unknown. This study investigates the relationship between underwater noise levels and harbour porpoise occurrence and potential foraging activity during the tow-to-port maintenance of turbines at Hywind Scotland. Passive acoustic click detectors were deployed along a gradient array from the wind farm, with broadband recorders positioned at two locations along the array. Sound pressure levels (derived from one-third octave bands spanning 25 Hz to 40 kHz) increased significantly during large-scale maintenance, particularly during towing and mooring work, with peaks up to 29 dB above routine operational averages. Concurrently, porpoise detections declined, particularly within 2 km of a turbine, with reductions of up to 33% at 600 m from the nearest turbine during periods of large-scale maintenance compared to routine operations. Detection rates increased once high-intensity activities ceased, suggesting effects were temporary. Potential foraging activity showed no consistent change, indicating that porpoises likely continued to forage when present. These findings provide the first evidence of ecological responses to tow-to-port maintenance at a floating wind farm and suggest that disturbance may be short-lived and spatially restricted. However, this may change as wind farm size increases, as maintenance operations are likely to involve more turbines and vessels, potentially extending the duration and spatial extent of disturbance. As floating offshore wind developments expand in size, continued monitoring will be essential to assess cumulative and longer-term impacts of maintenance activities and to support effective environmental management.

Keywords Offshore renewable energy, Behavioural disturbance, Underwater acoustics, Marine mammals, Tow-to-port, Operation and maintenance

Graphical abstract



Introduction

Offshore wind farms are often considered across three major stages of their lifecycle in relation to environmental impacts: construction, operation & maintenance, and decommissioning (Diederichs et al. 2008). For fixed offshore wind farms, construction and decommissioning typically involve the greatest noise disturbance from pile driving, seismic surveys, drilling, and increased vessel traffic (Bailey et al. 2014, Hall et al. 2022). These phases, however, are relatively short compared to the operation & maintenance phase, which constitutes the majority of a wind farm's lifespan; a normal wind farms lifespan is approximately 25

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years, whereas construction takes approximately 1–2 years. During operation, impacts are generally lower in intensity but may be chronic, with potential for both cumulative negative effects (Gușatu et al. 2021, Rezaei et al. 2023) and positive benefits such as reef effects that enhance prey availability (Degraer et al. 2020). Harbour porpoises typically avoid offshore wind farm areas during construction (Graham et al. 2023, van Geel et al. 2023, Voß et al. 2023), though the extent can be reduced if habituation occurs (Graham et al. 2019). Once turbines are operational, porpoise occurrence patterns during routine activity often return to pre-construction levels (Teilmann and Carstensen 2012). In certain cases, detection rates and foraging activity intensities have even increased from pre-construction levels at the sites, likely reflecting enhanced prey resources associated with reef effects (Scheidat et al. 2011).

However, for floating offshore wind farms, which are located in deeper waters further from shore, maintenance practices can differ substantially from those at fixed-bottom sites. While most routine maintenance and minor repairs are completed *in situ*, heavy maintenance that requires the replacement of large components may not always be feasible on site (Centeno-Telleria et al. 2025). Instead, a tow-to-port strategy can be employed, whereby the entire turbine is disconnected, transported to port for maintenance, and then returned to site (Hu et al. 2024, Centeno-Telleria et al. 2025). This approach requires deep-water ports capable of accommodating the large turbine substructures and specialist anchor-handling or towing vessels. Although tow-to-port procedures are possible for certain turbine designs, they are not expected to become the predominant maintenance approach; instead, *in situ* repairs are generally favoured wherever technically feasible (M. Boon, Equinor, pers.comm. 2026).

By the end of 2025, 278 MW of floating wind capacity had been installed worldwide, and global installations are projected to reach gigawatt scale by 2030 (GWEC 2025, 2026). The UK currently (as of May 2026) has 78 MW of floating offshore wind capacity, generated by two floating offshore wind farms: Hywind Scotland (operating since 2017; Equinor) and Kincardine (operating since 2021; Principle Power). Both wind farms are located on the North-East Scottish coast off Aberdeenshire. The tow-to-port operation for larger maintenance was successfully completed at the Kincardine site for one turbine in 2022 and another in 2023 (McLean 2023), demonstrating the feasibility of the approach. The following year, in 2024, all five turbines at Hywind Scotland were individually towed-to-port for maintenance. These operations mark a distinct shift in offshore wind maintenance practices compared with traditional fixed-bottom sites, potentially introducing new ecological impacts during the operational stage of a wind farm.

Although the impacts of tow-to-port maintenance are expected to be less severe than those associated with construction activities such as piling, they may still pose risks to marine ecosystems. The movement of platforms and moorings can disturb colonising epibenthic communities, which exhibit depth-related zonation (Karlsson et al. 2022), and potentially increase risk of transporting invasive or non-native species. Benthic species may also be affected where moorings and cables are re-laid and the seabed is disturbed. Additional underwater noise is likely to be generated during turbine detachment, platform movement, and vessel operations. Vessel presence itself can affect marine mammals through both physical disturbance and acoustic masking (Wisniewska et al. 2018, Pigeault et al. 2024); the additional vessels required for tow-to-port maintenance could potentially pose similar concerns. While operational noise resulting from rotating blades of floating wind farms is comparable to that of fixed-bottom wind farms (Risch et al. 2023), other operational noise at floating offshore wind farms differs from that of fixed sites due to the mooring structures (Burns et al. 2022, Risch et al. 2023). The presence of transient mooring noise varies depending on the design of the mooring structures and the materials used; some configurations generate substantial amounts of mooring-related noise, whereas others produce much less (Welch et al. 2025). During tow-to-port maintenance, the removal of platforms and laying down of moorings removes these sources of noise from the operational soundscape, with the extent of change depending on how many turbines have been towed away at any one time. Consequently, although vessel traffic will increase, other operational noise sources will be reduced. The behavioural responses of marine species to the transient mooring-related sounds, however, are not yet well understood (Risch et al. 2023, Harris et al. 2025).

As harbour porpoises are known to forage around offshore structures (Fernandez-Betelu et al. 2022), they may be particularly vulnerable to disturbance during such large-scale maintenance events (Wisniewska et al. 2016). However, given that floating offshore wind is a relatively new technology with only four operational sites, and a handful of demonstrators or single turbines (Edwards et al. 2023), the ecological impacts generally remain poorly understood (Harris et al. 2025), as do specific activities including the tow-to-port maintenance. The aim of this study was to quantify changes in underwater noise, and in harbour porpoise presence and potential foraging behaviour, during the tow-to-port of all five turbines at Hywind Scotland, compared with periods of normal operation and routine maintenance.

Methods

Study area and data collection

Data collection occurred at the Hywind Scotland floating offshore wind farm located 25 km from the Scottish east coast, in water depths of 100–130 m. The wind farm was constructed in 2017 and contains five 6 MW spar-buoy floating turbines connected to three moorings, each including one suction anchor, per turbine (Statoil 2015). The platform substructures have an operational draught of approximately 80 m (Statoil 2015). The seabed in the area contains mostly sand and gravel (Karlsson et al. 2022).

An array of seven moorings (M1–M7), equipped with passive acoustic monitoring (PAM) devices, was deployed in a gradient from the site extending south from turbine HS5 (Fig. 1). The closest mooring (M1) was 600 m from turbine HS5 with subsequent moorings spaced at regular 500 m intervals. The moorings were positioned along the axis of the predominant wind and tidal current flow (Statoil 2015). All moorings were deployed at depths of 105 m.

Each mooring contained two C-POD echolocation detectors (Chelonia Ltd) positioned vertically 1 m above each other at 4 m and 5 m from the seabed, respectively (Supplementary Fig. 1). Two C-PODs were used on each mooring to mitigate against premature failure of a device (Benjamins et al. 2017). Moorings M2 and M6 also contained broadband recorders (Song Meter SM2M, Wildlife

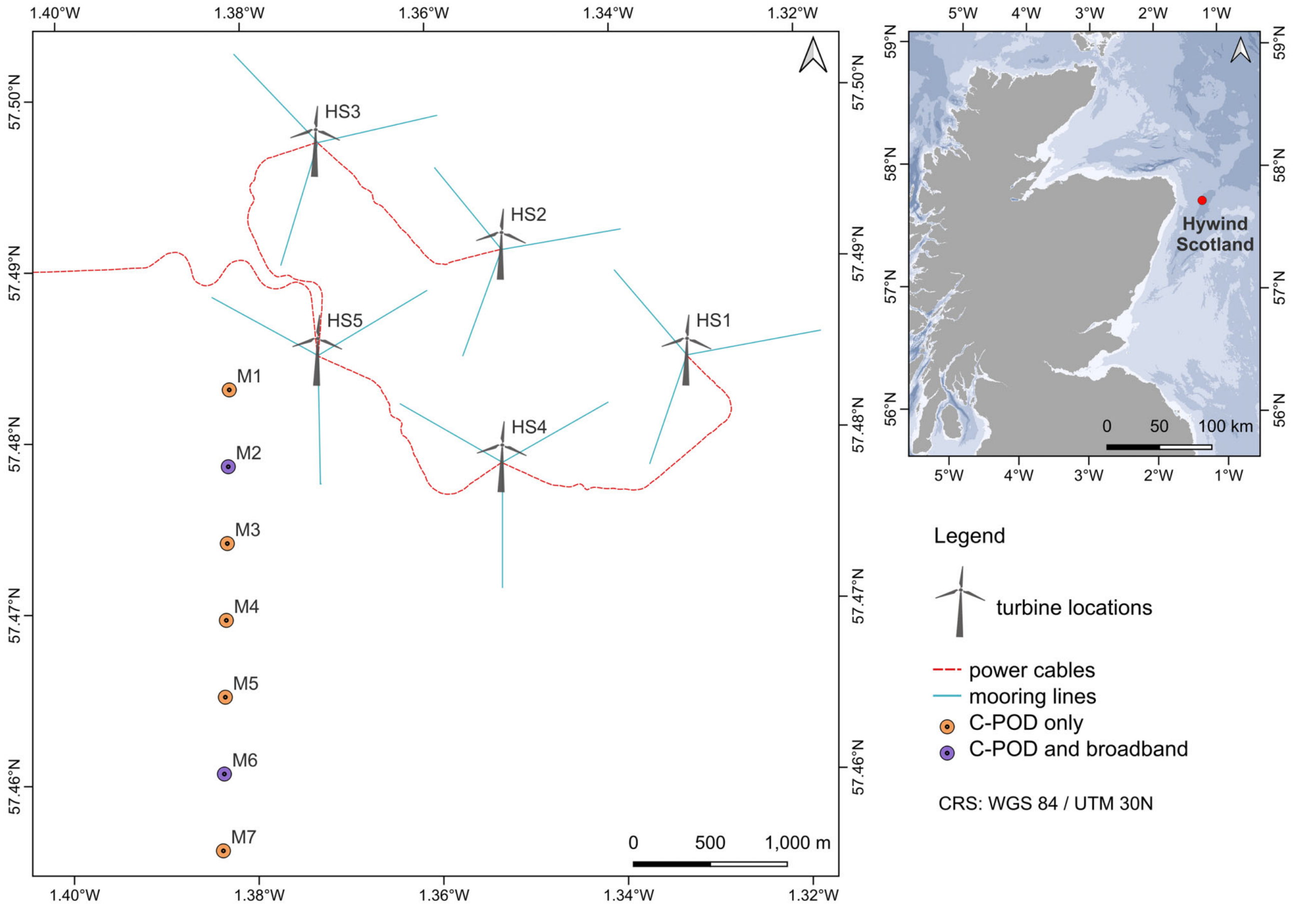

Figure 1 Mooring positions at Hywind Scotland floating offshore wind farm. All moorings (M1 - M7) extend south from turbine HS5 at regular intervals of 500 m. M1 is at 600 m from turbine HS5 while M7 is at 3300 m. Each mooring contained two C-PODs, M2 and M6 also contained broadband recorders (SM2M and ST300HF, respectively).

Acoustics Inc. and SoundTrap ST300HF, Ocean Instruments, respectively) positioned above the C-PODs at 6 m from the seabed. All moorings were deployed on 10 December 2023, recovered for servicing on 9 May 2024 and redeployed on 17 May 2024 until final recovery on 28 September 2024. This resulted in a deployment time of 285 days, or just under 10 months excluding servicing days. The mooring at M4 was not redeployed during the second deployment period due to battery issues with the acoustic release system (Supplementary Table 1).

Maintenance activity

All data on maintenance activities were provided by the site developer, Equinor ASA. Large-scale maintenance activities for the tow-to-port lasted between 18 April 2024 to 25 October 2024, the first turbine was towed away on 19 May 2024 (HS2), and the last turbine was back at the site on 18 September 2024 (HS1). There was some overlap in turbine absences, but at least two turbines always remained on site. Turbines were towed away from Hywind Scotland to the Wergeland port located in Gulen, Norway, as Scottish ports were of insufficient depth. Towing between the site and the port took approximately 5 days and each turbine spent an average of 46 days at Wergeland for servicing before being towed back to site.

To remove turbines from the site, several key steps were undertaken as described by the site developer. In brief, turbines were disconnected from the power grid and switched to generators for auxiliary power. Electrical cables were disconnected from the turbine and lowered to the seabed. Moorings were disconnected along the chain section, and the anchor-side of each mooring was lowered to the seabed and secured, allowing it to remain in place during the turbine's absence. The turbine platform was connected to tow ropes which were secured to three individual towing vessels as each mooring chain was disconnected. These vessels positioned themselves in a triangular formation around the turbine, each with a connecting point to the turbine. The three tow vessels (Table 1) then transported the turbine to Wergeland port where the maintenance work was carried out. Once completed, the process was reversed to return the turbine to site and reconnect all systems.

Vessel presence increased substantially during turbine removal and reinstallation periods**.** Up to nine vessels were present on site: five Crew Transfer Vessels (CTV), one Service Operation Vessel (SOV), and the three large towing vessels (AHV; Anchor-Handling Vessel) used during mooring disconnection/reconnection and towing operations (Table 1). In contrast, normal maintenance periods typically only involved a single vessel to carry out routine work at the site on a near-daily basis (vessel Swath, Table 1).

Table 1 Vessels used during maintenance activities, including unique identifiers (MMSI), vessel type and length, and the dates they were involved in maintenance works. (Source: Equinor ASA)

Vessel name	MMSI	Vessel type	Length	Time frame present at site
Swath	235 117 181/232 021 202	CTV	26 m	At all times
Viking	235 085 842	CTV	18 m	18/04/2024–05/05/2025 & 13/05/2024–22/05/2024
Island Diligence	258 687 000	SOV	86 m	19/04/2024–25/09/2024
Adventure	235 097 139	CTV	19 m	09/05/2024–19/05/2024
Goath Na Mara (GNM)	235 113 236	CTV	26 m	22/05/2024–21/09/2024
Esbjerg	219 023 786	CTV	39 m	22/09/2024–25/10/2024
Skandi Vega	257 403 000	AHV	110 m	Approximately 20 days∗
Normand Ferking	710 008 266	AHV	90 m	Approximately 20 days∗
Normand Sigma/Island Vanguard	259 827 000/259 121 000	AHV	87 m	Approximately 20 days∗

SOV = Service Operation Vessel
CTV = Crew Transfer Vessel
AHV = Anchor-Handling Vessel
∗AHVs were on site for approximately 2 days per turbine tow, resulting in an estimated total of 20 days per vessel, distributed throughout the large-scale maintenance period. Exact dates were unavailable.

Details on maintenance periods and the timing of specific maintenance activities were used to identify key periods of interest for analysis. Two broad categories were initially defined as “normal maintenance,” which included all routine operation and maintenance activities, and “large-scale maintenance,” defined as the period beginning with the arrival of the first additional vessel in preparation for turbine towing operations. An “after” period was not defined in this study, as the PAM array recovery coincided with the final stages of turbine reconnection to the grid and while additional vessels were still at the site.

Within the large-scale maintenance period, a further subdivision was made to capture variation in activity levels. Specific days involving significant infrastructure movement in the water column, and increased vessel presence, were identified as “major large-scale activities.” These activities included laying down and retrieving inter-array and export cables, disconnecting and reconnecting mooring lines, and towing turbines to and from the site. Remaining days were categorised as “other large-scale work,” where additional vessels were at the site and preparatory works were ongoing to remaining turbines. This classification resulted in three final categories for analysis:

1. “*Normal maintenance*”—routine maintenance prior to 18 April 2024 (when large-scale maintenance began).
2. “*Major large-scale activities*”—high-intensity days during the large-scale maintenance period when the specific operations described previously took place.
3. “*Other large-scale work*”—individual days within the large-scale maintenance period on which major activities were not occurring.

Noise analysis

Acoustic data were collected at the two mooring locations with broadband devices (SM2M at M2 and ST300HF at M6). Both devices recorded for ten minutes on the hour; the ST300HF recorded every hour, and the SM2M every other hour, both using 16-bit resolution and a 96 kHz sampling rate, allowing data to be analysed up to 48 kHz. No pre-amplifier gain was applied to the SM2M device. A full calibration of the devices was beyond the scope of this study. Instead, the most recent factory calibration settings were applied. The ST300HF had an end-to-end system sensitivity of − 174.1 dB re 1 μPa, while the SM2M hydrophone sensitivity was − 165.9 dB re 1 V/μPa. Because up-to-date, frequency-specific calibrations were not conducted, broadband values were used to assess relative changes in sound levels between periods rather than to report absolute sound pressure levels.

One-third octave level (TOLs) were calculated using PAMGuide, for centre frequencies between 25 Hz to 40 kHz over a 1-second time window (Merchant et al. 2015, Risch et al. 2023). Broadband sound pressure level (SPL; dB re 1 μPa) was derived from TOLs by summing energy across frequency bands in the linear domain and converting back to decibels. Hourly broadband SPL was then calculated as the median of the 1 s values, and daily SPL was calculated as the median of hourly values. Daily median SPLs for each device were modelled separately in Gaussian linear models as a function of the three maintenance categories identified (normal maintenance, major large-scale activities and other large-scale work). Differences between maintenance periods were additionally assessed using a Kruskal–Wallis test, and post-hoc Wilcoxon’s test (Conover 1999).

Hourly TOL SPLs were also calculated as the median of the 1 s TOLs. For each maintenance category, the median SPL across all hourly values was calculated for plotting to represent the typical spectral level within each frequency band across the recording period, with variability summarised using the 5th and 95th percentiles. Long-term spectral averages (LTSAs) were produced separately for representative high SPL days within each maintenance period using MATLAB. Power spectral density (PSD) estimates were calculated from short-time Fourier transforms of the recordings and subsequently aggregated by taking the median PSD within 10-s time bins to construct the LTSA matrix (Merchant et al. 2015). To visualise daily temporal patterns, LTSA plots were assembled by concatenating successive duty-cycle recordings (hourly or bi-hourly) within each day and plotted sequentially.

In addition, environmental variables (wind speed, wave height and current velocity) were obtained from Copernicus datasets (Copernicus Climate Change Service 2023, Copernicus Marine Service 2023, 2025) and used to compare conditions across maintenance periods to assess whether environmental variation could have contributed to observed changes in SPLs between periods (see Supplementary Material page 10 for details).

Porpoise analysis

As each mooring was equipped with two C-PODs, only one device was used per period to avoid duplication. Detection rates from paired devices were compared using heteroscedastic t-tests (Zar 1999), which showed that the top-mounted C-POD (approximately 1 m higher in the water column) recorded slightly higher detection rates at some moorings (M2–M6), whilst others showed no difference (M1 and M7). Given the aims of the study and the importance of maximising temporal coverage, a combined dataset was constructed by selecting, for each mooring and deployment period, the device with the longest recording duration. Where both devices had equivalent temporal coverage, data from the top-mounted C-POD were selected by default. To ensure that this selection did not bias results, analyses were conducted using both the combined "longest coverage" dataset and a reduced dataset containing only top-mounted C-PODs. Both approaches yielded consistent results across all models; therefore, the dataset with the greatest temporal coverage across maintenance periods was retained for final analyses, with C-POD position included as a model covariate. Most C-PODs were calibrated by the manufacturer (Chelonia Ltd) one month prior to deployment. Three of the C-PODs were not calibrated at that time, and these were used as back-up C-PODs on the bottom position of three of the moorings (Supplementary Table 1).

C-POD data were initially processed in the manufacturer's software CPOD.exe (version 2.044) (Chelonia Ltd 2025). Echolocation clicks were identified using the software's built-in KERNO classifier. Only click trains that were classified as of either "High" or "Moderate" quality were used in further analysis (Carlström 2005). Manual validation of individual click-trains was performed on 100 random sampling points for High and Moderate trains from each C-POD to ensure the absence of false positives (Benjamins et al. 2017), following guidelines from the manufacturer and previous studies (Chelonia Ltd 2013, Gauger and Taupp 2025).

C-PODs were programmed to stop recording during any minute if a predefined noise threshold was exceeded (default 4096 clicks per minute), resuming recording the following minute. This feature means that high levels of noise can saturate the C-PODs limit (Wilson et al. 2013) but was applied to prevent memory overload on the device and thereby optimising the data collection duration (Chelonia Ltd 2025). However, this "buffering" resulted in uneven sampling, with some minutes being underrepresented. As such, a conservative approach was taken, any minute that was not fully recorded was excluded, and any hour containing incomplete minutes was subsequently removed from the analysis. In total, 5% of hours were removed from the entire dataset (Supplementary Fig. 2).

Data were exported as detection positive hours (DPH), a binary indicator of whether harbour porpoises were detected in each hour. In addition, click details were also exported to assess buzz occurrence. Harbour porpoise buzzes are characterised by very short inter-click intervals (ICIs) and associated with foraging attempts. However, click trains with short ICIs are also produced in social context (Verfuß et al. 2009). As echolocation click trains with such short ICIs cannot currently be reliably distinguished between these behaviours using C-PODs, the approach by Pirotta et al. (2014) was used. A Gaussian Mixture Model was applied to log-transformed inter-click intervals. The model was fitted with three components, corresponding to short ICIs (buzzes), regular echolocation clicks, and longer inter-click intervals in between click trains. The component with the shortest mean ICI (approximately 10 ms) was classified as buzzes and considered here as a proxy for potential foraging activity, while acknowledging that these might also include social communication (Supplementary Fig. 3). Buzz-positive hours (BPH) were defined similar to DPH; if at least one buzz occurred within an hour, that hour was marked as buzz-positive. Daily porpoise presence was quantified as the proportion of DPH per day. Potential foraging activity was quantified as the proportion of BPH relative to the number of hours with porpoise detections (DPH). These proportions were used as daily metrics of presence and potential foraging accounting for variable sampling effort (i.e. due to the exclusion of some monitoring hours), and were used for subsequent modelling (Fernandez-Betelu et al. 2024).

Two separate Generalized Additive Models (GAMs; *bam* function from R package *mgcv)* (Wood 2015), were created to investigate the daily proportion of detection-positive hours and buzz-positive hours from all monitoring stations. Distance to the location of turbine HS5 was used as a fixed spatial reference point and modelled as an interaction with maintenance period, recognising that the turbine was absent from the site during part of the deployment. In both models, maintenance period (normal maintenance, major large-scale activities, and other large-scale work) and C-POD position (top/bottom) were included as parametric terms. Given that distance was sampled at only seven discrete levels, the basis dimension for the distance smooth was constrained to $k = 7$. Date (as a numeric variable) was included as a univariate smooth to account for broad seasonal and temporal variation in detection probability. A thin-plate regression spline was used, with $k = 10$ chosen to capture the dominant seasonal trend while avoiding over-adjustment and excessive complexity (Wood 2017, Amundin et al. 2022). Both GAMs were fitted using a binomial distribution with a logit link and estimated using restricted maximum likelihood (REML).

Temporal autocorrelation of the model residuals was checked using autocorrelation *(acf)* and partial autocorrelation *(pacf)* functions. The presence model showed small peaks decaying across the first few lags, suggesting minor temporal autocorrelation within successive days (Supplementary Fig. 4). To account for this, the model was refit using a first order autoregressive (AR1) structure (Wood 2017). Data were ordered by time for each mooring, and correlation was modelled only within contin-

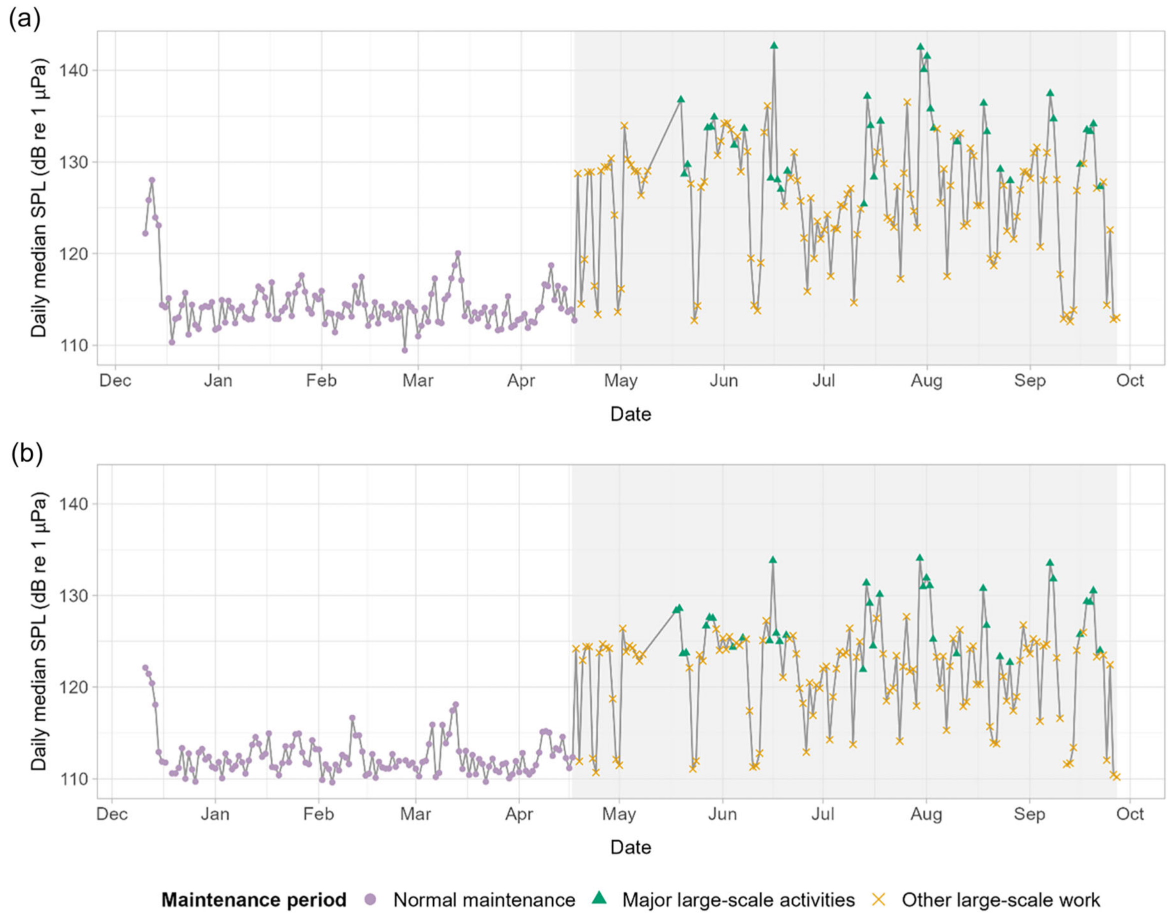

Figure 2 Daily averaged sound pressure levels (SPL) recorded at M2 (SM2M), approximately 950 m (a) and at M6 (ST300HF), approximately 2800 m (b) from the nearest turbine (HS5). The large-scale period begins on 18 April and is indicated by the shaded background. Maintenance periods are further classified so that days assigned to "normal maintenance" = circles, "major large-scale activities" = triangles (e.g. turbine towing and dis/re-connecting mooring lines), and "other large-scale work" = crosses.

uous temporal segments for each mooring, with the autoregressive structure reset when gaps of more than one day occurred (reflecting the temporal gap between data collection periods). The AR1 parameter (rho) was estimated from model residuals (rho = 0.375) and was used in the final model. No significant temporal autocorrelation was observed in the buzz model, and therefore no autoregressive correlation structure was included (Supplementary Fig. 5). Concurvity among smooth terms was assessed using the *concurvity* function in the *mgcv* package, and all observed values were low (< 0.2), indicating minimal redundancy among predictors. Model diagnostics were assessed using standard GAM diagnostic plots and basis-dimension checks, which indicated no major violations of model assumptions (Supplementary Figs 6 and 7).

To visualise how detection and potential foraging probability varied with distance across maintenance periods, predicted probabilities and 95% confidence intervals were generated from the fitted GAMs (Zuur et al. 2009, Wood 2017). Predicted distance-response curves were generated by holding other covariates constant to visualise the effect of the focal variables only (Lombardo et al. 2019, Pedersen et al. 2019). Prediction plots were generated for the top C-POD position and at the median date of each dataset (17 April for the presence model and 20 April for the buzz model).

Results

Variation in noise levels

The normal maintenance period spanned 129 days, the major large-scale activities period 36 days, and the other large-scale work period 118 days. SPLs (25 Hz to 40 kHz) were consistently lowest during the normal maintenance period (December to mid-April), with values typically ranging between 112 and 120 dB re 1 μPa at both broadband mooring locations (M2: approximately 950 m from HS5; M6 approximately 2800 m from HS5; Fig. 2). Noise levels increased during the large-scale maintenance period, with peaks coinciding with major activities (Fig. 2; green triangles), reaching up to 29 dB higher compared to the normal maintenance median. SPLs remained elevated during other large-scale work (Fig. 2; orange crosses), though generally lower than during major activities, and at times reflecting normal maintenance levels.

A Kruskal-Wallis test showed a significant effect of maintenance period on daily median SPLs at both M2 (χ^2= 175.16, df = 2, p < 0.001) and M6 (χ^2= 169.6, df = 2, p < 0.001). Pairwise Wilcoxon tests confirmed that all maintenance periods differed significantly from one another at both M2 and M6 (all

$p < 0.001$; Fig. 3). Linear modelling indicated that mean daily SPL increased by approximately 19 dB and 15 dB during major large-scale activities at M2 and M6, respectively, and by 10 dB and 8 dB during other large-scale work, relative to normal maintenance conditions.

Long-term spectral averages from both the SM2M (Fig. 4) and ST300HF (Fig. 5) recorders showed consistent differences in broadband sound levels among maintenance periods, although variability within these days occurred. Spectral levels were lowest during normal maintenance and elevated during periods of large-scale activities, particularly at lower frequencies. Major large-scale activities exhibited the highest sound levels across much of the spectrum, while other large-scale work showed intermediate levels between the two periods. These patterns were reflected in the one-third octave band summaries, which showed higher sound pressure levels during major large-scale activities across approximately 25 Hz to 10 kHz, with the largest differences observed below approximately 1 kHz. Other large-scale work showed the same trend but at intermediate levels between the two maintenance groups. Differences between maintenance periods decreased at higher frequencies (> 10 kHz), where spectral levels converged. Because the LTSA panels included in the TOL composite figures (Figs 4, 5) represent the noisiest days within each maintenance period, additional LTSA examples for representative median and low SPL days (when considering SPL across all recorded frequencies over an entire day) within each maintenance period are provided in the Supplementary Material for comparison (Supplementary Fig. 8; Supplementary Fig. 9).

Variation in porpoise presence and foraging

Harbour porpoises were detected every day along the PAM array throughout the study. In total, 65 196 hours of continuous pre-processed data were collected across all C-PODs along the gradient (two per mooring). As only one C-POD was used per mooring to avoid duplication, the analysis dataset contained 37 830 hours of data across 283 days. Of these, 1927 hours (approximately 5%) were excluded from the analysis based on the scan limit criteria.

The parametric effect of maintenance period indicated that detection probability was significantly lower during major large-scale activities compared to normal maintenance (estimate = -0.51 ± 0.17 SE, $p < 0.01$), while no significant difference was observed during other large-scale work ($p = 0.75$). The effect of distance on detection probability varied during major large-scale activities (edf = 2.61, $p < 0.001$), and other large-scale work (edf = 4.57, $p < 0.001$), but not during normal maintenance (edf = 2.09, $p = 0.19$; Fig. 6a; Supplementary Table 2).

During both large-scale maintenance periods, predicted detection probability decreased towards the site. During major large-scale activities, predicted detection probability decreased from approximately 0.57 at the furthest distance from HS5 (3300 m) to 0.37 at the closest distance (600 m), representing an approximate 35% decrease. During other large-scale work, predicted detection probability decreased from approximately 0.63 at the furthest distance to 0.48 at the closest (approximately 24% decrease). In contrast, during normal maintenance, predicted probability showed no significant change with distance (0.57 to 0.54). The largest difference between the maintenance periods occurred within approximately 2 km of the site. At the closest monitoring location (600 m from turbine HS5), predicted detection probability was approximately 33% lower during major large-scale activities relative to normal maintenance. Differences between major large-scale activities and the other maintenance periods decreased with distance, with predicted detection probabilities converging and confidence intervals overlapping beyond approximately 2–2.5 km. Numerical date and recorder position were also retained in the model. Detection probability varied significantly over time, peaking in August, and was higher at top-mounted devices (both $p < 0.001$; see Supplementary Table 2, Supplementary Fig. 10).

Maintenance period was not a significant predictor of porpoise buzz (potential foraging) behaviour (all $p > 0.24$; Fig. 6b; Supplementary Table 3). The effect of distance was significant during normal maintenance (edf = 1.27, $p < 0.001$), but no significant relationship with distance was observed during major large-scale activities (edf = 1, $p = 0.39$) or other large-scale work (edf = 1, $p = 0.29$). Overall, predicted buzz probability remained relatively constant across the study area, with minimal differences between maintenance periods and substantial overlap in confidence intervals (Fig. 6b). Similar to the presence model, numerical date was a significant predictor ($p < 0.001$), also peaking in August, and higher detections at top-mounted devices compared to bottom-mounted devices ($p < 0.001$; see Supplementary Table 3 and Supplementary Fig. 11).

Discussion

Maintenance data and changes in noise levels

Daily averaged SPLs were consistently lower during normal maintenance than during both large-scale periods. Major activities such as cable/mooring work or turbine towing increased SPLs by an average of 15–19 dB, with peaks up to 29 dB above the turbine operation and normal maintenance average. During the 154-day large-scale maintenance period, vessel activity was elevated, with an additional eight vessels recorded at the site in contrast to normal maintenance. Specific anchor-handling vessels (AHVs) were required for turbine towing and mooring work (Erbe et al. 2019, Saeed et al. 2022), indicating an increase in both vessel presence and infrastructure movement on major large-scale activity days.

The LTSA and TOL composite plots (Figs 4, 5) also show elevated broadband sound levels during the large-scale activity periods particularly from 25 Hz to 10 kHz and pronounced at lower frequencies (< 1 kHz). This pattern is consistent with vessel-dominated noise, characterised by elevated broadband SPLs and pronounced low-frequency components associated with increased vessel activity (Baldachini et al. 2025). Similar patterns have been reported during construction and decommissioning of offshore structures, including offshore wind, where vessel noise is a dominant contributor to the local soundscape (Hall et al. 2022, Benhemma-Le Gall et al. 2023, Fernandez-Betelu et al. 2024).

In contrast, during normal maintenance, the soundscape is influenced by turbine operational noise and mooring-related noise. Turbine noise is typically low frequency and comparable to that of fixed offshore wind (Burns et al. 2022, Risch et al. 2023), while

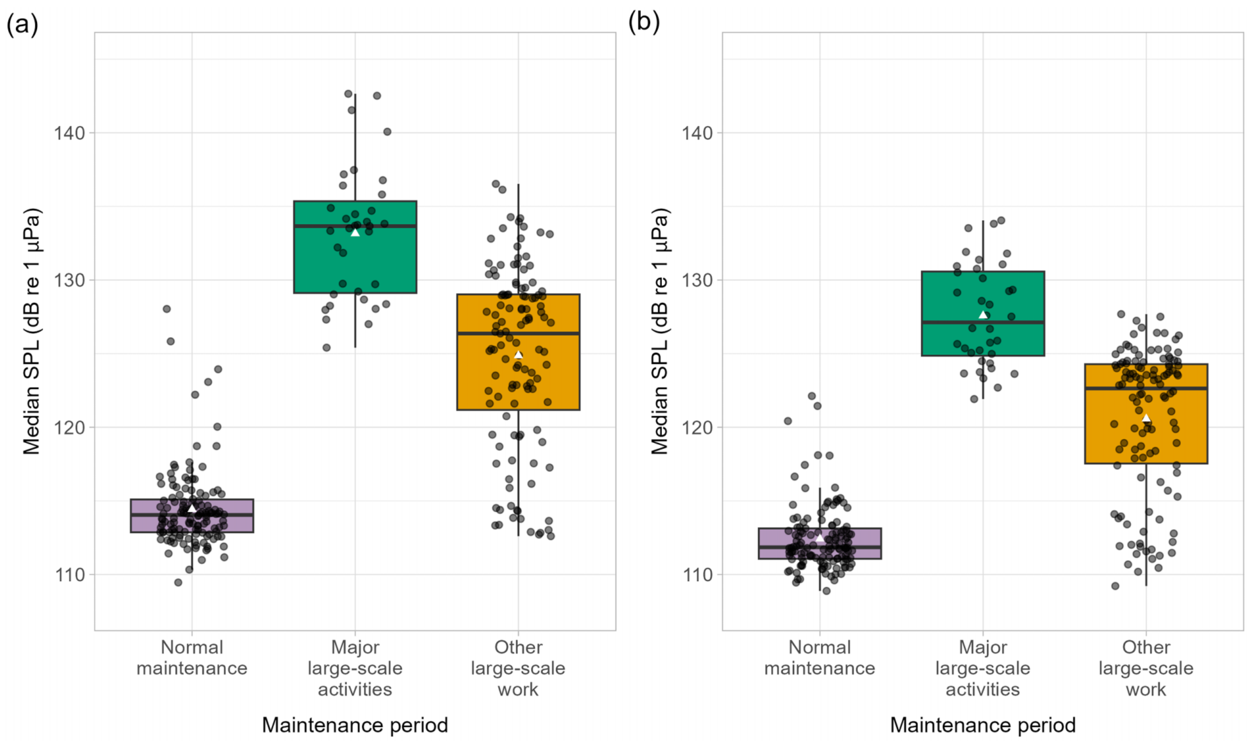

Figure 3 Comparison of average sound pressure levels (SPL) across maintenance periods at mooring M2 (SM2M), approximately 950 m from turbine HS5 (a) and M6 (ST300HF), approximately 2800 m from turbine HS5 (b). Boxes show the interquartile range with the median as the central line, the mean indicated by a white triangle, and raw data points as grey circles.

mooring-related noise varies between sites and mooring design (Welch et al. 2025). Mooring-related noise is characterised by transient "snaps" that increase with wind speed, are present across higher frequency ranges (10–48 kHz), and have been detected at Hywind Scotland (Burns et al. 2022, Risch et al. 2023). Consequently, during tow-to-port maintenance, turbine operational and mooring-related noise will be reduced or fully removed, while vessel activity and associated maintenance operations increase, resulting in a temporary alteration of the site's soundscape. It is therefore likely that the increase in vessels and associated increases in their activity largely contributed to the elevated SPLs observed. However, the coarse temporal resolution of the maintenance dataset (daily scale) prevented direct attribution of SPL increases to specific vessels or activities within the present study. SPLs at M6 (2800 m from turbine HS5) followed the same temporal pattern as those at M2 (950 m from turbine HS5), although absolute noise levels were lower (Fig. 2). Because different recording systems were used and were not calibrated, noise levels at each monitoring location and direct comparisons between locations, should be interpreted cautiously and considered primarily in terms of relative changes within each location. In addition, the number and type of vessels, the specific activity they are engaged in, and their distance from the recording equipment will influence measured SPLs, contributing to variability in observed SPLs. An analysis of turbine-specific decommissioning or recommissioning noise characterisation was not possible for this study due to simultaneous work occurring across turbines.

Higher noise levels may also result from increased wind speed, wave height and current velocity (Wenz 1962, Basan et al. 2024). However, tow-to-port maintenance operates under restrictive weather conditions, and will only occur in calm conditions (Schwarzkopf et al. 2020), thus environmental conditions were expected to be equal or better compared to normal maintenance work. Wind speed, wave height and current velocity were compared across the three maintenance periods, confirming that major large-scale maintenance occurred during calmer conditions, while normal maintenance periods included more variable and, at times, more energetic conditions (Supplementary Fig. 12). So, while these environmental factors will have contributed to the overall soundscape during all three maintenance phases, it was considered that the increases in noise measurements predominantly reflected maintenance-associated signals.

Harbour porpoise presence response

Harbour porpoise detection probabilities were higher during normal maintenance than during major large-scale activities, with no overall difference between normal maintenance and other large-scale work. During normal maintenance, there was little variation along the distance gradient from turbine HS5 (Fig. 6a). In contrast, during major large-scale activities, detection probability increased with distance, rising from 0.37 at the closest acoustic mooring (M1; 600 m from HS5) to 0.57 at the furthest mooring (M7; 3300 m from HS5). Correspondingly, at the closest mooring (M1; 600 m), detection probability was approximately 33% lower during major large-scale activities compared to normal maintenance.

The construction phase of offshore wind farms is typically the period associated with the greatest concentration and intensity of

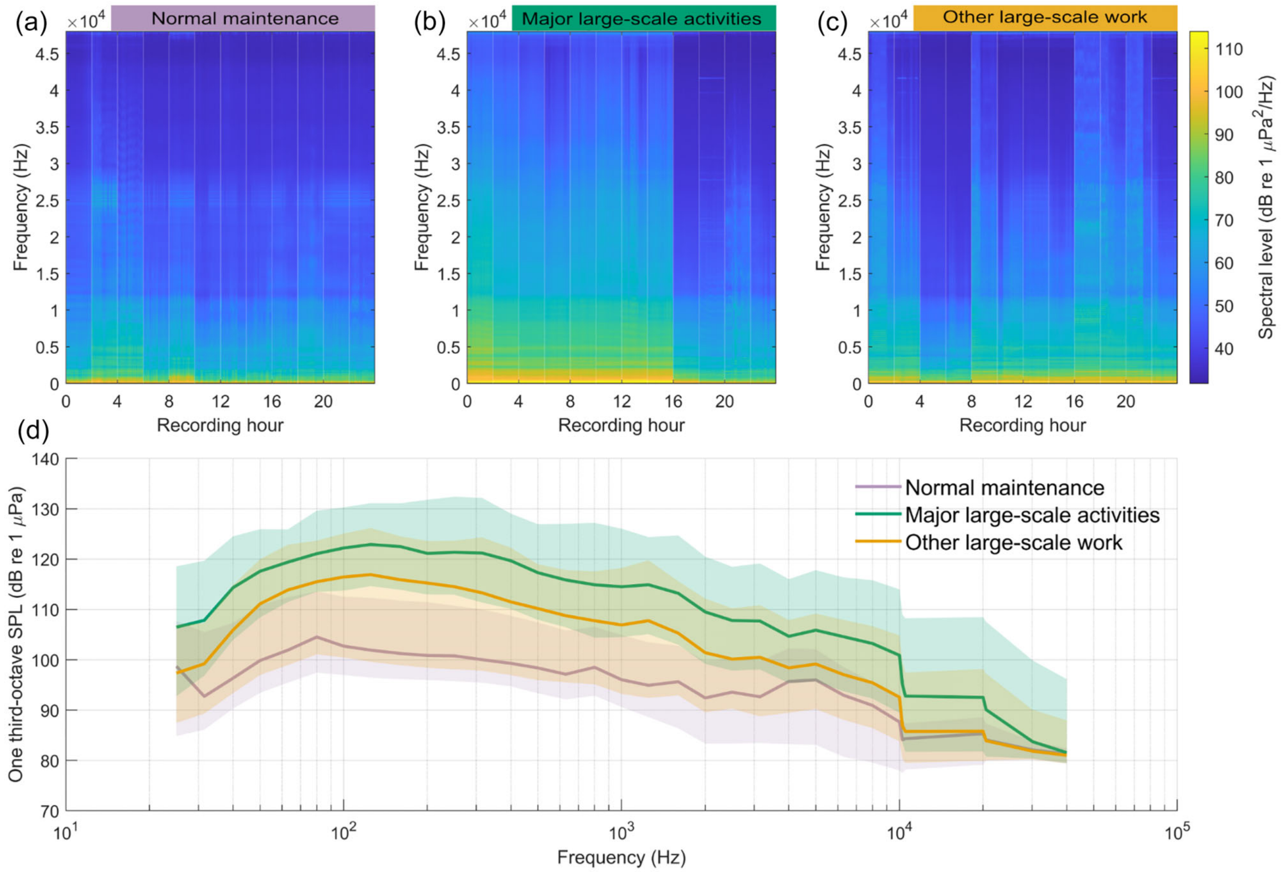

Figure 4 Composite plot showing frequency-dependent noise levels across maintenance periods recorded at Mooring 2 (SM2M), approximately 950 m from the nearest turbine (HS5). (a–c) show long-term spectral average (LTSA) plots for representative high sound pressure level (SPL) days across the frequency range within each maintenance period (12 December, 16 June, 26 July respectively). Spectra were calculated using a Hann window (FFT size = 2048 samples) with 50% overlap (hop size = 1024) and averaged over 10-s intervals. LTSA panels represent concatenated 10-min duty-cycled recordings across the day; white vertical lines indicate boundaries between individual recordings, and the x-axis shows recording hour. (d) shows median 1-s third-octave band SPLs (solid lines) for each maintenance category, with shaded bands indicating the 5th–95th percentile range.

vessel activity (Bailey et al. 2014, Paterson et al. 2018). However, the present study demonstrates that tow-to-port maintenance of floating turbines can also substantially increase vessel presence (Table 1), leading to elevated disturbance during the operational phase. Previous studies have reported harbour porpoise displacement from construction-related vessel activity at distances of up to 4 km (Benhemma-Le Gall et al. 2021), with broader spatial avoidance of vessel traffic observed at distances of up to 7 km (Wisniewska et al. 2018) and 9 km (Pigeault et al. 2024). Consistent with these findings, porpoise detection probability during major large-scale activities was reduced relative to other maintenance periods, particularly within 2 km of the site, with differences diminishing with distance and predicted probabilities converging beyond 3 km (Fig. 6a). However, it should be noted that distance was measured relative to a fixed reference point (the nearest turbine location), rather than the location of the disturbance source, which may influence the spatial interpretation of these patterns.

Behavioural responses of harbour porpoises to vessel disturbance include deeper diving, increased swimming speed, directional changes, and reductions or cessation of echolocation (Dyndo et al. 2015, Wisniewska et al. 2018, Frankish et al. 2023). As such, the observed reduction in acoustic detections may reflect a decrease in porpoise presence, a reduction in echolocation activity, or a combination of both. These responses may increase energetic costs, disrupt communication and social interactions, and reduce foraging efficiency, with potential implications for individual fitness if disturbances are frequent or prolonged (Dyndo et al. 2015).

However, detections increased during periods of other large-scale work when towing vessels were absent and the highest intensity work wasn't taking place, suggesting that these effects are likely temporary. This pattern indicates that behavioural responses, such as avoidance and/or reduced echolocation, may be short-lived and closely linked to high-intensity vessel presence and activity.

Harbour porpoise potential foraging response

When porpoises were present, buzz activity remained low (< 50%) and showed no significant difference between maintenance periods and little variation over distance (Fig. 6b). However, C-POD detection ranges are reduced for buzzes due to their lower source levels compared to regular echolocation clicks (DeRuiter et al.

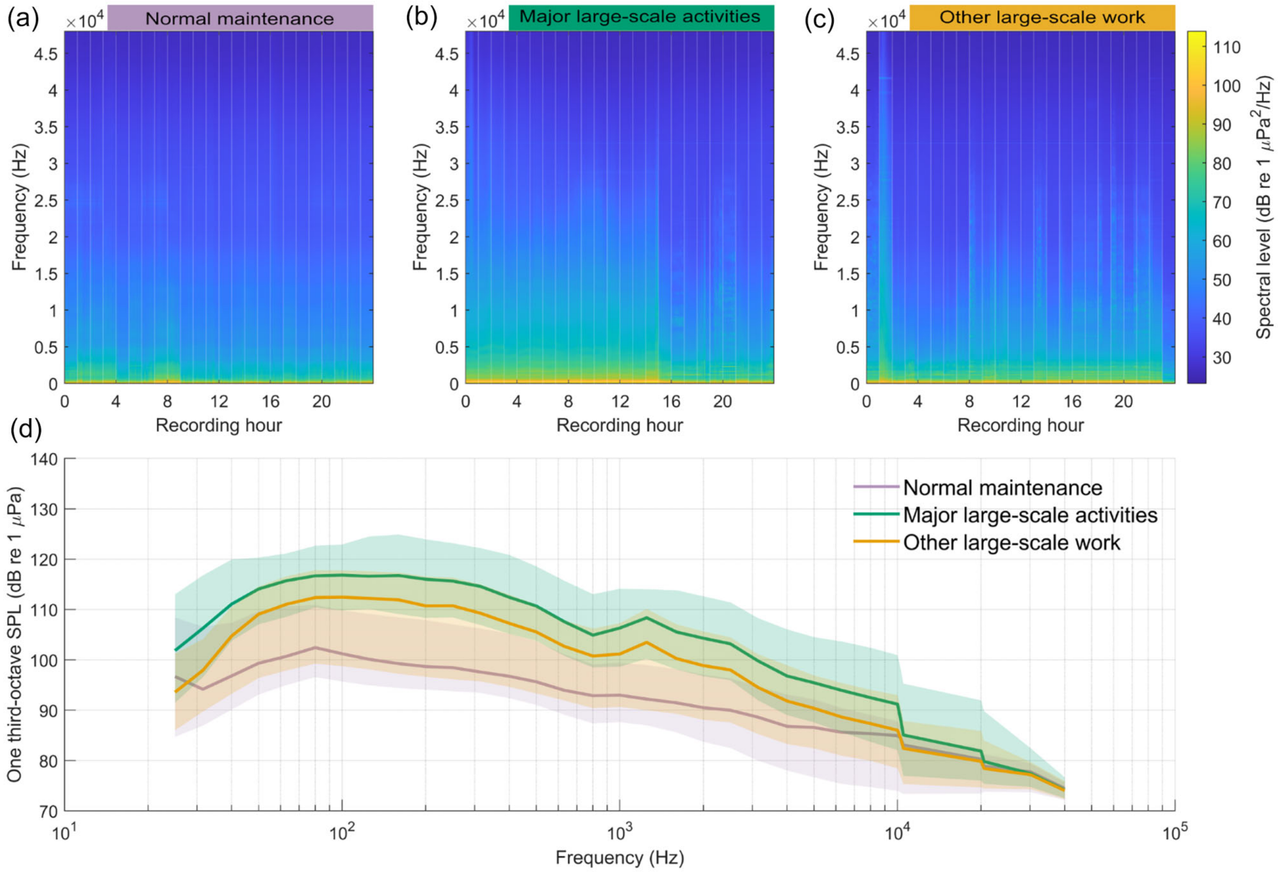

Figure 5 Composite plot showing frequency-dependent noise levels across maintenance periods recorded at Mooring 6 (ST300HF), approximately 2800 m from the nearest turbine (HS5). (a–c) show long-term spectral average (LTSA) plots for representative high sound pressure level (SPL) days across the frequency range within each maintenance period (12 December, 16 June, 26 July respectively). Spectra were calculated using a Hann window (FFT size = 2048 samples) with 50% overlap (hop size = 1024) and averaged over 10-s intervals. LTSA panels represent concatenated 10-min duty-cycled recordings across the day; white vertical lines indicate boundaries between individual recordings, and the x-axis shows recording hour. (d) shows median 1-s third-octave band SPLs (solid lines) for each maintenance category, with shaded bands indicating the 5th–95th percentile range.

2009, Todd et al. 2023), and the more focused direction of buzzes towards prey rather than scanning (Verfuß et al. 2009, Stedt et al. 2024). As a result, buzz detections (and hence potential foraging behaviour) are likely underrepresented in this type of data (Todd et al. 2023). Despite this limitation, the overall consistency in foraging probability suggests that when porpoises were present, potential foraging behaviour was maintained across maintenance periods. A comparable pattern has been reported during the decommissioning of an oil and gas platform, where overall harbour porpoise detections declined within 2 km, but foraging activity was only slightly reduced within 1 km, and unaffected at 200 m (Fernandez-Betelu et al. 2024). This suggests that while animals may reduce their presence or vocalisation rates in disturbed areas, when present and vocalising, potential foraging may occur at a similar scale.

As harbour porpoise presence is largely driven by foraging opportunities (Stedt et al. 2023), both occurrence and buzz detections at the site are likely influenced by prey availability. The limited change in buzz detections between maintenance periods may reflect the high metabolic demands of harbour porpoises, which require frequent feeding to meet energetic requirements (Wisniewska et al. 2016). In addition, spatial memory of previously successful foraging locations may continue to draw individuals back despite disturbance (Nabe-Nielsen et al. 2013, Iorio-Merlo et al. 2022). Together, these findings highlight the importance of distinguishing between occurrence and behaviour when assessing responses to disturbance, as potential foraging activity appeared less affected in this study than presence alone.

Another consideration during tow-to-port maintenance is the potential impact of turbine removal on habitat structure and potential prey availability. Floating turbine sub-structures can enhance local mixing through turbulence and wakes in the water column which may enhance primary productivity and influence prey aggregation (Dorrell et al. 2022, Floeter et al. 2022, Karlsson et al. 2022). In addition to noise-related disturbance, the temporary removal of these structures during tow-to-port maintenance may therefore also reduce local mixing and potentially alter prey availability, although any resulting ecological changes may not occur immediately and have not been quantified in the current study. Future studies investigating concurrent changes in hydrodynamics and prey availability during such maintenance operations would help clarify whether these processes influence porpoise use of floating offshore wind farms, and any resulting changes during their removal, in addition to potential disturbance from vessels and maintenance works.

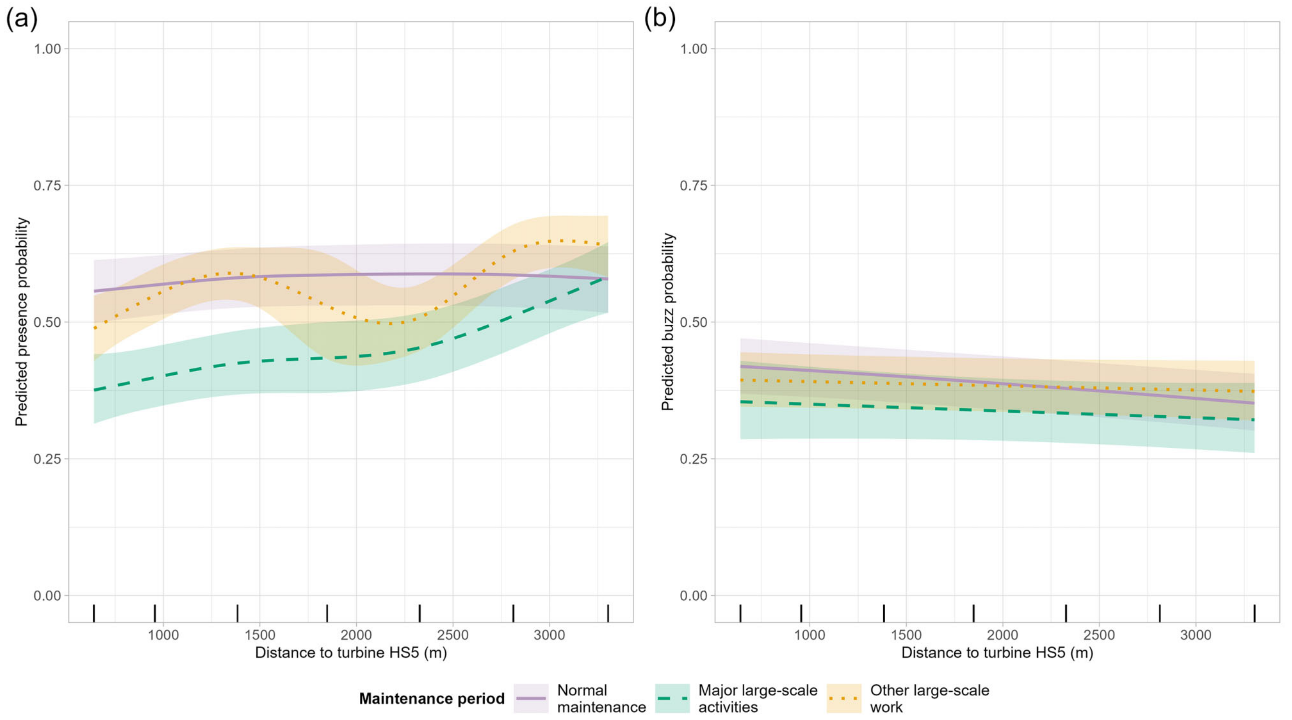

Figure 6 Predicted probabilities of harbour porpoise presence (a) and potential foraging (b) along the distance gradient from the nearest turbine (HS5) across maintenance periods. Rug marks indicate the distances of the acoustic moorings.

Management considerations

These results indicate that porpoise vocalisation detection rates are reduced during major maintenance activities, such as mooring or cable work and turbine towing, particularly within 2 km of the site. However, detection rates increased during large-scale maintenance once these higher-impact activities ceased, suggesting that potential disturbance may be relatively short-lived. Vessel activity at fixed offshore wind farms can reduce porpoise detection rates (Graham et al. 2019), even prior to the start of piling during construction (Benhemma-Le Gall et al. 2023). This suggests that proximity to vessels at offshore wind sites could elicit behavioural responses. Therefore, the number of vessels at the site, the specific activity they are engaged in, and the length of time spent at site, could exacerbate impacts on harbour porpoises. In this study, each turbine required an average of four days in total of AHV presence for mooring/cable work and towing for both dis- and re-connection. This relatively limited number of days per turbine demonstrates that minimising the time at site for large vessels and the most intensive work is achievable in practice and offers a positive example for future management of floating offshore wind farms. Hywind Scotland is a relatively small site of only five turbines; as the number of turbines increase in new developments, naturally, the amount of vessel time at the site will also increase. Concentrating work efficiently and limiting the number of vessels involved could therefore help reduce impacts as the number and size of sites grow.

In this study, undertaken at a specific location and based on the number, combination, and locations of vessels incorporated here, porpoise detections returned to levels observed during routine maintenance by 3 km from turbine HS5, suggesting that the spatial extent of disturbance may be more limited than that reported for higher-intensity construction activities such as pile driving (Tougaard et al. 2009, Dähne et al. 2013, Brandt et al. 2016). Although the observed impacts on harbour porpoises site usage appear to be relatively short-lived and mainly contained to periods of major large-scale activity, repeated or cumulative exposure to disturbance, both from the tow-to-port operation, across other offshore developments, and industrial and recreational activities, may still result in longer-term consequences. Tow-to-port maintenance operations at floating offshore wind are infrequent as they are only conducted when large repairs are required that cannot currently be completed in-situ (Centeno-Telleria et al. 2025), though this may change with continued advances in technology and maintenance practices allowing increased repairs on site (Bayati and Efthimiou 2021). Therefore, at a site of this size, the tow-to-port maintenance is not likely to result in long-term impacts on site use. However, the effects could differ at larger sites, through cumulative impacts, or at more critical sites that see high levels of porpoise activity including important feeding areas.

Therefore, several factors should be considered as floating offshore wind developments expand globally, including increasing site size and number of sites which could contribute to cumulative effects. Larger sites may require more frequent and longer maintenance periods and increased numbers of vessels, particularly if multiple turbines undergo maintenance and towing simultaneously. In addition, sites further from shore will require longer tow distances to suitable ports, requiring vessel traffic over larger regions. Suitable ports require depths deep enough to accommodate the large turbine substructures and towing vessels; therefore, towing distance may vary substantially from site to site. Wergeland port (Norway), where turbines were towed to in this study was located approximately 450 km from the wind farm, and towing occurred over five days. The impact of increased vessel traffic to/from the site was not incorporated into this study. The potential impacts of such increased or sustained vessel activity during towing operations should therefore be investigated as the number and size of developments increase, given evidence that porpoises avoid areas with frequent vessel traffic (Benhemma-Le Gall et al. 2021, Pigeault et al. 2024). Site characteristics, including turbine size and design, mooring configuration and water depth, may influence impacts by affecting the number and size of vessels required, the duration of maintenance activities, and potential changes in porpoise behaviour in deeper waters (Brandt et al. 2014, Frankish et al. 2023). As floating offshore wind expands, it is recommended that operators collaborate and share experience to optimise efficiency, thereby reducing time on site, maintenance costs, and environmental impacts. Maintenance planning could also consider the seasonal occurrence of key species, to avoid periods of high site use and further minimise potential ecological disturbance where operationally feasible, while recognising that such maintenance is constrained by weather conditions which may limit the practicality of seasonal scheduling (Schwarzkopf et al. 2020). As more developments become operational, ongoing studies across sites of varying sizes, turbine and mooring designs, and depths, will be essential to improve understanding of large-scale maintenance impacts and support the consenting of new developments.

Limitations and future work

Due to C-PODs briefly ceasing to log click-like signals when oversaturated with noise (Wilson et al. 2013), only fully monitored hours were retained for analysis. Similar approaches are often used with C-POD data to ascertain that only fully (or near fully) monitored hours are incorporated in the analyses and thereby decreasing the probability that a lack of detections results from decreased monitoring effort (Brandt et al. 2018, Fernandez-Betelu et al. 2022, van Geel et al. 2023, Fernandez-Betelu et al. 2024). These exclusions coincided with the noisiest conditions, particularly during large-scale maintenance activity (Supplementary Fig. 3), therefore, the missing hours are not evenly distributed across the dataset. However, removing these periods reduces the potential influence of elevated noise levels on click detectability. The overall proportion of data removed was small (5% of the entire data set and generally $< 10\%$ per mooring), meaning that while some bias may have been introduced by disproportionately reducing coverage during noisy periods, the dataset still captures the vast majority of recording effort, and obtained results are underpinned by robust data. Notably, this exclusion applied to the porpoise data only, whereas the noise analyses include all recorded conditions.

The maximum detection range of C-PODs is around approximately 400 m, although the effective detection radius (i.e. the distance at which as many detections are detected within that range as are missed beyond that radius) is typically closer to 200 m (Nuuttila et al. 2018, Todd et al. 2025). Detection probability is also influenced by animal behaviour and orientation relative to the device, due to the highly directional nature of porpoise echolocation beams (Koblitz et al. 2012, Macaulay et al. 2023). As a result, it is not possible with C-POD click detectors alone, to separate the mechanisms responsible for reduced detections such as porpoise behaviour or reduced detection capability in circumstances of increased broadband noise levels. However, to minimise the influence of noise on detection probability, hours in which the default click threshold was exceeded were excluded, and detections were modelled at a coarse temporal resolution of presence/absence per hour (Benhemma-Le Gall et al. 2021). This approach reduces the impact of short-term reductions in detection rates, as only a single click train is required to register presence within each hour.

The coarse temporal resolution of currently available maintenance data, along with simultaneous work occurring across the site, prevented attribution of porpoises' responses to specific events. Future work should consider incorporating a more detailed assessment of vessel-specific noise, along with integrating vessel tracking data (e.g. Automatic Identification System; AIS), higher resolution data on the timings of maintenance activities, as well as including comparisons of operational and mooring-related noise levels when turbines are removed from the site. Key factors likely to influence responses include the type and number of vessels present (and associated noise output), the number and proximity of turbines under maintenance, and the relative positions of vessels to the acoustic monitoring stations. Understanding these dynamics is particularly important when extrapolating results from small, closely spaced sites such as Hywind Scotland to larger floating offshore wind farms. Expanding studies to larger wind farms as they become operational, and including pre- and post-maintenance monitoring, would further improve understanding of both short- and long-term effects. In addition, propagation modelling (Putland et al. 2018, Risch et al. 2023, Baldachini et al. 2025) could help distinguish between normal operational noise levels and periods of large-scale maintenance, including contributions from vessel activity and the removal of turbine operational and mooring-related noise. Such models can also account for spatial and temporal variability in sound propagation driven by environmental conditions (Baldachini et al. 2025). Consequently, including vessel-, activity- and turbine-specific noise outputs, and modelling received sound levels across monitoring locations, would allow porpoise presence and potential foraging activity to be assessed in relation to exposure, rather than distance from the nearest turbine. Although distance from turbine HS5 was a significant parameter in the models, a direct measure of received noise levels may better represent disturbance at the monitoring locations, as it incorporates variability driven by vessel number, activity, and spatial configuration relative to the acoustic recorders. Expanding gradient arrays across multiple positions at the site, as well as extending the distance over which is being monitored (especially for larger farms where impact ranges might be expected to be increased), would also help understand if this pattern is consistent site-wide, and allows the full spatial extent of impact to be assessed. Additionally, fine-scale behavioural monitoring methods such as multi-channel arrays that allow for localisation (Graham et al. 2023) would contribute to a deeper understanding of behavioural changes in relation to the wind farm. In relation to this, as porpoises are known to produce click trains with short inter-click intervals during both foraging and social activity, research to distinguish these in acoustic data would be extremely useful and would increase our capability to assess behavioural impacts from anthropogenic activities, including from wind farm maintenance, on harbour porpoise.

Prey availability is likely to influence detections independently of maintenance. While this study discussed potential changes in habitat structure and prey availability, these processes were not directly measured. Future work should adopt a more holistic approach, incorporating concurrent assessments and changes of predator and prey dynamics, as well as hydrodynamic conditions, to better understand how large-scale maintenance activities influence ecosystem processes around turbines.

Conclusion

This study provides the first evidence of harbour porpoise responses to large-scale maintenance of tow-to-port operations, at a floating offshore wind farm in Scotland. Noise levels were substantially increased during these activities, particularly on days during which major large-scale activities such as turbine towing, mooring, and cable work, took place.

Harbour porpoise detection probability was reduced during major activities particularly within 2 km of the nearest turbine location (whether the turbine was in place or not), with effects diminishing at a distance of $\geq$ 3 km. These effects appeared short-lived, as porpoise presence was less affected during other large-scale maintenance periods when vessel numbers and activity intensity were lower. Notably, potential foraging probability remained largely unchanged, indicating that porpoises continue to forage when present despite temporary disturbances. The results highlight that maintenance activities can cause localised, temporary behavioural changes (either through avoidance or reduced vocalisation) without substantial changes in the proportion of hours containing potential foraging activity.

The findings provide considerations for management and monitoring. Concentrating high-disturbance activities into short periods, limiting vessel numbers, and timing operations to avoid sensitive periods for species of concern may help reduce impacts. However, tow-to-port maintenance is constrained by favourable weather conditions and the need to minimise turbine downtime, and is therefore typically limited to periods of calm weather. In this study, intensive tow-to-port operations involving AHVs were completed within a short timeframe (approximately four days per turbine in total), demonstrating that minimising the duration of high-intensity work is achievable in practice. Such efficiencies may help reduce impacts while also being economically advantageous. However, as floating offshore wind farms increase in size, maintenance operations are likely to involve more turbines and vessels, potentially extending the duration and spatial extent of disturbance. Continued monitoring, including pre- and post-maintenance periods, will therefore be important to assess both short- and longer-term responses and to inform effective mitigation strategies as floating offshore wind development continues to expand.

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Author contributions

Caitlin B Harris (Conceptualization [lead], Data curation [lead], Formal Analysis [lead], Investigation [lead], Methodology [lead], Visualization [lead], Writing—original draft [lead], Writing—review & editing [equal]), Steven Benjamins (Conceptualization [supporting], Formal Analysis [supporting], Funding acquisition [equal], Methodology [supporting], Project administration [supporting], Supervision [supporting], Writing—review & editing [equal]), Nienke van Geel (Formal Analysis [supporting], Methodology [supporting], Writing—review & editing [equal]), Ellen White (Methodology [supporting], Visualization [supporting], Writing—review & editing [equal]), Beth E Scott (Conceptualization [supporting], Formal Analysis [supporting], Funding acquisition [equal], Methodology [supporting], Project administration [supporting], Supervision [supporting], Writing—review & editing [equal]), and Benjamin J Williamson (Conceptualization [supporting], Formal Analysis [supporting], Funding acquisition [equal], Methodology [supporting], Project administration [lead], Supervision [lead], Writing—review & editing [equal])

Supplementary material

Supplementary data is available at *ICES Journal of Marine Science* online.

Conflicts of interest

None declared.

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Data availability

Data will be made available on request.

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