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ORIGINAL PAPER

Offshore construction using gravity-base foundations indicates no long-term impacts on dolphins and harbour porpoise

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Abstract

There are concerns about the short- and long-term effects on cetaceans from offshore construction using pile-driving. Gravity-base foundations and anchored floating turbines are alternative installation methods that may have less impact on cetaceans. In this study, we investigated the response of dolphins (*Tursiops truncatus* and *Lagenorhynchus albirostris*) and harbour porpoise (*Phocoena phocoena*) to the construction of wind turbines using gravity-base foundations off Blyth, Northumberland, United Kingdom using cetacean echolocation recorders (C-PODs). Data were collected at nine sites across 3 years (2016–2018) before, during and after construction. Generalised additive mixed models were used to investigate temporal, environmental, and anthropogenic drivers of dolphin and porpoise occurrence from 143,215 h (5967 days) of C-POD data. The models explained 27% and 30% of the deviance in dolphin and porpoise occurrence, respectively. Overall, the results showed no long-term effect on the dolphin occurrence from the construction of the gravity-base wind turbine array. In contrast, porpoise occurrence increased by 32% and 75%, respectively, in the years during and after construction, compared to the before-construction year. Other predictors of dolphin and porpoise occurrence included month, hour of day, tidal currents and vessel sonar activity. Our findings indicate that wind turbine installation using gravity-base foundations had no long-term effects on the occurrence of dolphins or porpoise and may represent an offshore construction methodology that is less impactful to dolphins and harbour porpoise than impact pile-driven turbine installation methods. These results are important for future offshore energy developments; however, further studies are recommended to investigate potential species and location variations.

Keywords Odontocete · Marine mammal · Wind farm · Renewable energy · Pile-driving · United Kingdom

Introduction

The global energy sector is rapidly expanding to meet increasing energy demands. Driven by international agreements to combat climate change and increasing fossil fuel prices, energy production is gradually transforming to renewable sources including solar and wind (Kåberger 2018). In the European Union (Directive 2018/2002/EU), renewables are required to contribute at least 32% of Member States' energy production by 2030 (European Union 2018) and the United Kingdom has also retained similar targets following its exit from the EU, such as reducing its greenhouse gas footprint by 80% by 2050 (Barton et al. 2018). In 2019, 84% of the global capacity of offshore wind was located within European waters (Best and Halpin 2019) and UK wind energy accounted for 9.5% of all electricity generated in 2020 (Stebbings et al. 2020).

Offshore wind developments require more substantial infrastructure compared to on-land developments (e.g. anchoring to the seabed) and may cause physical and acoustic disturbance to marine ecosystems and species, particularly during the construction phase (Duarte et al. 2021). Toothed whales (i.e. odontocetes), such as dolphins and porpoises, produce high-frequency echolocation signals for navigation and prey detection, and lower frequency sounds for

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communication (Au 1993). Anthropogenic activities including offshore construction may interfere with toothed whale echolocation and communication through acoustic masking, compromising the animals' use of sound (Richardson and Würsig 1997), and may cause deterrence and behavioural changes (Tougaard et al. 2009; Brandt et al. 2018). Temporal and spatial habitat displacements of harbour porpoise (*Phocoena phocoena*) have been demonstrated in previous studies with animal impact distances of 15–21 km from the offshore construction sites (Carstensen et al. 2006; Brandt et al. 2011; Scheidat et al. 2011). To mitigate the impacts of acoustic disturbance, animals may change frequency and/or increase the amplitude of the sounds they use, stay silent until the disturbance has terminated or move away from the source of the disturbance (Richardson and Würsig 1997; Nowacek et al. 2007; Miller et al. 2014). However, these mitigation options come with the cost of increased energy demand and/or missed opportunities for foraging and social interaction. In addition, prolonged or sudden exposure to loud noise can cause damage to the animals' hearing tissues and lead to temporary or permanent threshold shifts (Southall et al. 2009, 2019; Bailey et al. 2010). Therefore, when developing offshore energy structures, such as wind turbines, the potential for short- and long-term health effects on animals and ecosystems need to be considered and appropriately mitigated.

The construction of offshore wind turbines involves three phases: pre-installation surveys, construction and operation. During the pre-installation phase, the development site is comprehensively surveyed using vessel-based visual, acoustic and/or other survey methodologies to determine bottom substrate, presence of any obstructions and Unexploded Ordnances/Munitions and Explosives of Concern (UXOs/MECs), and to assess marine flora and fauna diversity, occurrence and abundance. The construction phase includes foundation installation and other related activities (e.g. removal of UXOs/MECs, piling, drilling, dredging, seabed preparation, cabling and anchoring) that are specific to the site and the turbine construction method chosen by the developer. During the operational phase, the wind turbines require regular maintenance facilitated by vessels transporting personnel to conduct above and underwater checks of the structures. Whilst operational, wind turbines produce broadband noise levels in the region of 170–177 dB re 1 m Pa sound pressure level root mean square (SPL_{rms}), primarily at frequencies below 1 kHz, based on a 10-megawatt (MW) turbine generator and levels will vary depending on the size, power, modernisation of the gearbox and specifications of the turbines (Tougaard et al. 2020; Stöber and Thomsen 2021).

All phases of wind turbine development may cause acoustic disturbance, though the construction phase is likely the most intensive. Major impacts of pile-driven construction and other construction-related activities can include permanent or temporary auditory damage (Lucke et al. 2009; Kastelein et al. 2016), changes in toothed whale occurrence patterns (Thompson et al. 2010) and habitat displacement (Brandt et al. 2011; Dähne et al. 2013). In some locations, harbour porpoises have responded to pile-driven construction with long-term area avoidance (Teilmann and Carstensen 2012). Yet, in other areas, following an initial reduction harbour porpoises returned to, and even exceeded, before-construction levels of occurrence (Scheidat et al. 2011), suggesting that responses may be location specific. Despite variation in the short- and long-term responses of toothed whales to pile-driving, there is a clear risk for a negative impact from the use of an impact pile-driving installation approach.

Gravity-based foundations offer an alternative to pile-driving, with no need for percussive or vibratory hammering (Ruiz de Temiño Alonso 2013). Gravity-based foundations consist of a concrete base into which the shaft of the turbine is installed (Esteban et al. 2019). The concrete foundation is manufactured onshore, towed as a floating platform or transported by vessel to the installation site where it is positioned and submerged onto the seabed (Jiang 2021). The platform is submerged by being filled and ballasted with water, sand and/or gravel to prevent scour and maintain structural integrity (Reach et al. 2014). Seabed preparation is required prior to installation and involves the removal of sediment to level the seabed conducted by dredging or screeding (Esteban et al. 2015, 2019). Soft sediment dredging is known to produce continuous, broadband sounds concentrated at lower frequencies, generally < 1 kHz at source levels ranging between 111 and 189 dB re 1 μPa rms (Reine et al. 2014; Todd et al. 2015; Wenger et al. 2017). Thus, the use of gravity-based foundations may reduce the level of acoustic disturbance to toothed whales and offer a less impactful construction methodology.

The aim of this study is to investigate the impacts of wind turbine construction using gravity-base foundations on the occurrence of toothed whales (dolphins and harbour porpoise).

Materials and methods

Study area

This study was conducted off the coast of Blyth, Northumberland, United Kingdom (N55.131°, W1.402°) in the North Sea. The depth in the area ranges between 10 and 50 m and the bottom substrate is predominantly a mix of soft sediments (i.e. sand, mud, and gravel). Between April and October 2017, EDF Renewables' Blyth Offshore Demonstrator (BOD) project installed five offshore turbines (8.3-MW

MHI Vestas V164 models which are referred to as an "array" herein), 191 m high with a rotor diameter of 164 m using gravity-base foundations (EDF 2017). Gravity-base foundations are steel-reinforced concrete bases which support steel monopiles. The construction activities associated with the foundations (i.e. seabed preparation) were conducted in May and June 2017 and turbine installation was conducted between July and October 2017. For installation, the BOD was the first development to use the novel "float and submerge" technique where the gravity-base foundations were built on shore; towed and positioned at the installation site whilst being kept afloat by vessels (i.e. tugboats to eliminate the need for heavy-lift crane vessels); and then sunk and ballasted (using seawater pumped into the foundation) with scour protection placed around the foundation base (EDF 2017). At the time of installation, BOD represented the deepest application of gravity-based foundations (approximately 40 m) since the construction of the Thornton Bank Wind Farm in the Belgian part of the North Sea (Mathern et al. 2021). The array was fully commissioned and operational (i.e. started generating energy to the power grid) in June 2018 (4C Offshore 2018).

The Northumberland BOD site is frequented by common bottlenose dolphins (*Tursiops truncatus*), white-beaked dolphins (*Lagenorhynchus albirostris*), and harbour porpoises, species which could be impacted by the construction and operation of wind turbines in this area. To effectively monitor the dolphin and harbour porpoise presence around the BOD site, archival passive acoustic monitoring (PAM) devices were deployed around the array and nearshore environment. The utilisation of PAM to monitor for toothed whale echolocation has proven an effective tool for assessment of dolphin and harbour porpoise spatial and temporal occurrence and behaviour (Dede et al. 2014; Roberts and Read 2015; Nuuttila et al. 2018). Further, PAM effectiveness is not significantly impacted by factors that may hamper visual surveys, including daylight, weather condition, visibility, sea state and observer bias, to monitor toothed whale presence (Barlow et al. 2001). However, whilst PAM systems result in large quantities of high-quality data, most are not be able to distinguish among some species (e.g. delphinid spp.), and may underrepresent species presence based solely on their acoustic behaviour as the animal must be producing sounds to be detected (Mellinger et al. 2007; Gibb et al. 2019).

Data collection

Nine cetacean echolocation recorders (C-PODs; www.chelonia.co.uk) were used to monitor the "occurrence" of dolphins and harbour porpoise (i.e. the acoustic presence) at the BOD site between January 2016 and September 2018. The deployment period covered the before- (January 2016–March 2017), during- (April–October 2017), and after-construction (November 2017–September 2018) phases (Fig. 1, Table 1) at the turbine installation site. C-PODs are autonomous passive acoustic monitoring recorders that store data from high-frequency echolocation clicks (20–160 kHz) at a minimum resolution of 5 µs. C-PODs do not currently allow for acoustic differentiation between common bottlenose and white-beaked dolphin echolocation clicks and click trains. This is a result of both delphinid species utilising broadband clicks with similar acoustic characteristics (Rasmussen and Miller 2002; Yang et al. 2021). Whilst the bottlenose dolphin is the most regularly sighted of the two species in the area, the contribution of white-beaked dolphins to the occurrence data cannot be ignored. For the subsequent analyses, both species are treated as a singular category (hereafter referred as "dolphins"). C-PODs were deployed ≥ 1.5 km apart to ensure independence of collected data. C-PODs were anchored 4 m above the seafloor (in order to minimise the potential interference of benthic noise), using a 30 kg concrete weight connected by a 120 m grappling line to a secondary anchor and surface buoy. C-PODs were serviced monthly to download data and replace batteries if needed.

Data extraction and management

Data were processed through the Generalised Encounter Classifier (GENENC) within the C-POD companion software, C-POD.exe v2.044, (Chelonia Ltd., Cornwall, United Kingdom, www.chelonia.co.uk). The GENENC classifier is designed for maximal separation of narrowband, high frequency (porpoise), broadband (dolphin) click trains and vessel sonar (Tregenza 2013; Robbins et al. 2016; Jaramillo-Legorreta et al. 2017). Only detections categorised as high quality were used in the analyses in order to minimise the likelihood of false positives. In addition, only hours in which a full 60 min of sampling occurred were utilised in the analyses, in order to maximise the reliability of the data used. Hours with less than 60 min of sampling per hour represented only 2.28% of hours monitored. Detection Positive Minutes (DPMs; a minute in which at least one click train was detected) hour^{-1} were used to investigate spatial and temporal variation in relative occurrence of dolphins and harbour porpoises. All data were stored in a PostgreSQL database v9.6.2 (PostgreSQL Global Development Group 2017) allowing information to be sorted and extracted using custom-written Python scripts (Python Software Foundation 2016). Statistical analyses were carried out in R v3.30 + and associated packages, using R Studio v2022.07.0 + 548 (R Core Team 2019).

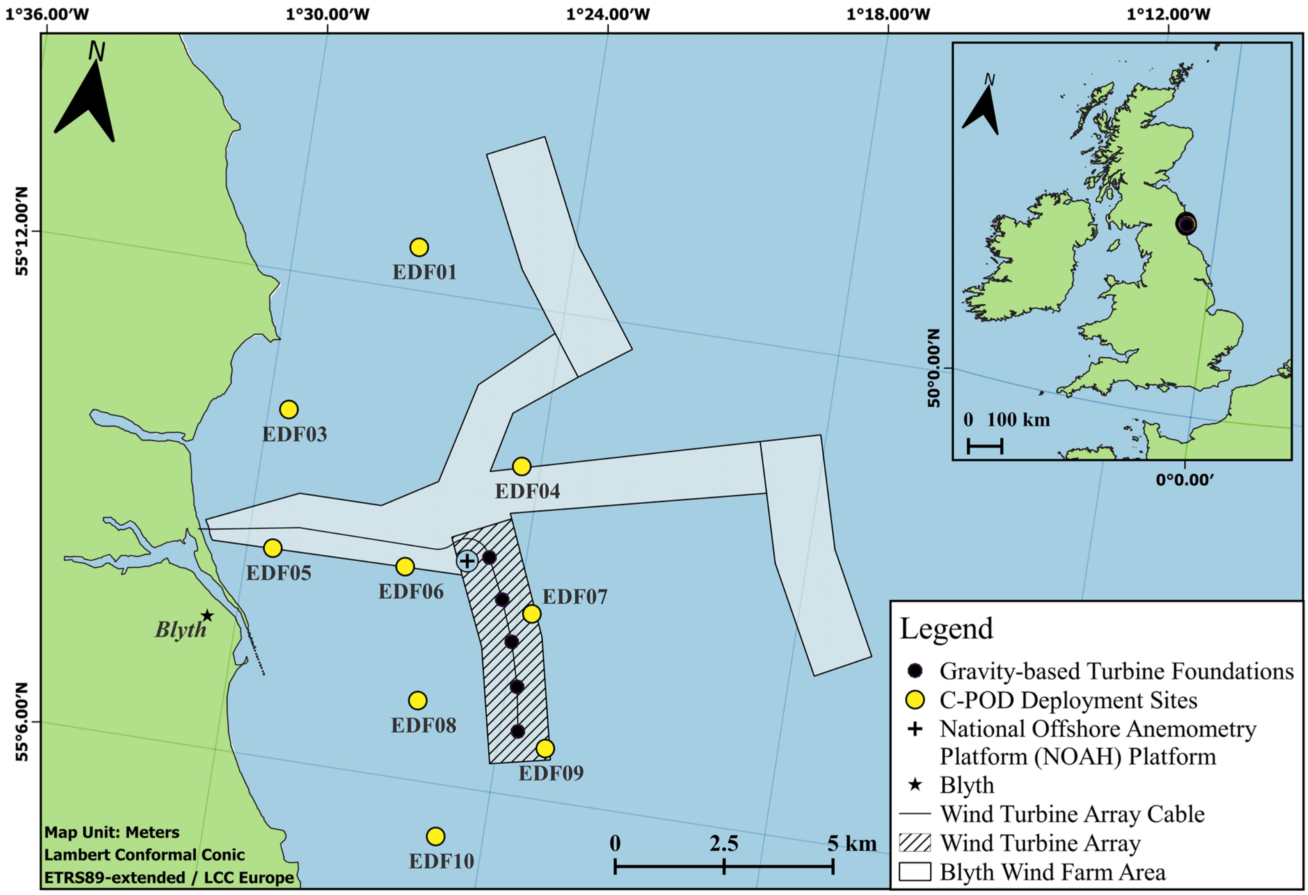


Fig. 1 The deployment locations of the nine cetacean echolocation recorders (C-PODs) used to monitor occurrence of dolphins and harbour porpoise during the development of EDF Renewables' Blyth Offshore Demonstrator wind turbine array off Northumberland, United Kingdom

Table 1 Details for position, start and end dates, water depth, bottom type, and monitoring time for all nine C-POD deployment locations

Site name	Latitude (DDM)	Longitude (DDM)	Water depth (m)	Deployment start (dd/mm/yyyy)	Deployment end (dd/mm/yyyy)	Hours monitored before construction	Hours monitored during construction	Hours monitored after construction
EDF01	55 12.528	– 1 27.221	40	01/03/2016	24/06/2018	9569	3108	4505
EDF03	55 10.305	– 1 29.495	11	13/04/2016	17/09/2018	7347	3107	2168
EDF04	55 10.056	– 1 24.286	44	09/03/2016	17/05/2018	7891	4185	2844
EDF05	55 8.587	– 1 29.343	12	01/03/2016	03/04/2018	8121	4185	2701
EDF06	55 8.601	– 1 26.454	33	01/03/2016	03/05/2018	9405	5130	4304
EDF07	55 8.262	– 1 23.635	41	01/03/2016	09/04/2018	8612	4398	3824
EDF08	55 6.989	– 1 25.752	32	09/03/2016	24/04/2018	8067	3846	3046
EDF09	55 6.659	– 1 22.886	40	09/03/2016	24/04/2018	5159	3880	4183
EDF10	55 5.349	– 1 24.908	32	01/03/2016	19/05/2018	9707	5133	4790

Variable selection, analyses, and model selection

A selection of temporal, environmental, and C-POD-extracted variables were considered in the analyses (Table 2). The temporal variables included in the analyses were year, month, hour and construction phase. The extracted variables from C-POD.exe included dolphin, harbour porpoise and vessel sonar occurrence. Oceanographic variables for bottom water salinity, bottom water temperature, bottom current velocity and bottom current direction were obtained from the Copernicus data hub (https://www.copernicus.eu/en; *NORTHWESTSHELF_ANALYSIS_FOR-*

Table 2 Variables used in the GAMM analysis and the rationale for why some variables were included or not included

Variable type	Variable	Resolution of variable	Rationale for inclusion
Temporal variable	Construction	Before, during, after	To allow analyses of construction impacts
	Year	2016, 2017, 2018	To allow analyses of inter-annual variability in other variables
	Month	Numeric	To represent inter-annual monthly and/or seasonal changes
	Hour	Numeric	To represent the diel changes throughout the 24-h cycle
C-POD.exe variables	Dolphin	DPM/hour	To understand impacts to dolphin species
	Harbour porpoise	DPM/hour	To understand impacts to harbour porpoises
	Sonar	DPM/hour	To understand the influence of construction vessels/other vessels on species
	C-POD location	EDF01, EDF03, EDF04, EDF05, EDF06, EDF07, EDF08, EDF09, EDF10	Fit as a random effect to examine the impact of construction across the general area
Environmental variables	Bottom water salinity	Hourly	Given the shallow depth of the site, bottom data are considered representative of generalised patterns. Surface measures are directly affected by, e.g. winds and rain
	Bottom water temperature	Hourly	
	Bottom current velocity	Hourly	Grouped together as these interact mechanistically and form a proxy for tidal currents
	Bottom current direction	Hourly	

CAST_PHY_004_013 Atlantic—European North West Shelf—Ocean Physics Analysis and Forecast dataset; Tonani et al. 2019). Some variables, such as depth and distance from shore, were not included in the models as they were collinear with the C-POD deployment locations.

Data were analysed using generalised additive mixed models (GAMMs) in the *mgcv* package (Wood and Wood 2015). GAMMs were considered appropriate as relationships between dependent and independent variables were not expected to be linear and so variable smoothing was likely to be required. Furthermore, the distribution of the dependent variables considered are liable to result in violation of the assumption of residual normality required for non-generalised models. GAMMs were fitted with negative binomial (DPM/Hour), binomial and quasibinomial families (proportional DPM/Hour). Binomial and quasibinomial families were able to account for the upper bounding of the data (i.e. there is a maximum of 60 DPM hour^{-1}), which the negative binomial distribution cannot. The family providing the best model fit was selected using deviance explained. The potential for temporal (*ar1*) error structures in the models were considered. C-POD location was included as a random effect variable to allow analyses of overall occurrence patterns across the BOD site.

All independent variables were assessed for evidence of multi-concurvity (multicollinearity without the linear assumption), i.e. when one independent variable can be predicted by the other independent variables to a non-trivial degree, using GAMMs with a $R \leq 0.5$ as the allowable threshold. If evidence of multi-concurvity was found, selection between concurve variables was made on the basis of the functional value and practical usability of the variables in question. Bottom temperature showed a high degree of concurvity with month. Month reflects the intra-annual fluctuation in water temperature, and it is a possible correlate of important processes such as prey species availability and is more applicable for use in environmental management planning and regulatory governance. Thus, bottom temperature was excluded and month was retained for subsequent analyses.

Variables were fitted using cubic regression splines with the exception of both hour and bottom current direction, which were fitted using cyclic cubic regression splines. Bottom current velocity and bottom current direction were fitted as a tensor product smooth, creating a singular smooth term representing tidal currents. The tidal current smooth is imperfect, as it is constrained by the current inability to apply soap film splines to data on different scales—which would otherwise better reflect the hard boundaries of the direction and velocity interaction (i.e. some tidal velocities can only be reached as the tide moves in specific directions). The interactions of month and hour were fit using isotropic smooths for their main effects (i.e. individual variable effects) and tensor smooths for their marginal effects (i.e. combined variable effects), thus accounting for the potential effects of intra-annual variability in hours of light and darkness in addition to the isolated effects of month and hour. The main effect of month was fit by year to allow exploration of potential changes in intra-annual monthly patterns of occurrence between construction phases and the main effect of hour was fit by construction phase to allow examination of any potential change. *k*-value selection was iterative following guidance from Wood and Wood (2015). To reduce the likelihood of overfitting, *gamma* was set to 1.4 and a maximum allowable *k*-value was set at 20. Both significant and non-significant variables were retained in the model (Whittingham et al. 2006).

Results

The study resulted in a total of 143,215 complete hours (5967 days) of monitoring across all nine C-POD locations between January 2016 and September 2018 (Table 1). Collectively, recordings contained 14,642 DPMs spread over 1992 h for dolphins and 476,293 DPMs spread over 42,886 h for harbour porpoise across all locations. The deployment periods of the C-PODs at each monitoring location are shown in Supplementary Information 1.

The best fitting GAMMs explained 27.0% of the deviance for dolphin occurrence and 30.2% for harbour porpoise occurrence (Table 3). The selected model for dolphins utilised the negative binomial family and for harbour porpoise, the model utilised the quasibinomial family. In general, the results showed that there was no change in the overall occurrence of dolphins during the study and that there was an increase in occurrence during and after construction for harbour porpoise compared to before construction (Table 3). The main drivers affecting the occurrence of dolphins were the temporal factors (month, month:hour), location and vessel activity, although the latter had relatively lower effect (Table 3). For harbour porpoise, the main drivers affecting the occurrence were the temporal factors (construction phase, month:hour and month), tidal current (current velocity and direction), location, dolphin and vessel activity, but the latter had relatively less effect (Table 3).

Table 3 Summaries for dolphin and harbour porpoise generalized additive mixed models

Smooth terms	Smooth	Spline	edf	*F* value	*p* value	Parametric coefficients	Estimate	*t* value	*p* value
Dolphins									
Porpoise	s	cr	1.00	128.62	< 0.001	Intercept (before construction)	−7.77	−14.838	< 0.001
Sonar (vessel)	s	cr	2.16	14.23	< 0.001	During construction	−0.32	−1.44	0.151
Month (2016)	s	cr	10.23	31.78	< 0.001	After construction	0.74	1.39	0.164
Month (2017)	s	cr	8.73	18.33	< 0.001				
Month (2018)	s	cr	4.95	11.12	< 0.001				
Hour (before construction)	s	cc	4.71	43.56	< 0.001				
Hour (during construction)	s	cc	5.15	17.02	< 0.001				
Hour (after construction)	s	cc	3.95	19.30	< 0.001				
Month:hour	ti	cr:cc	18.57	1.75	< 0.001				
Current velocity and direction	te	cr:cc	4.62	1.50	0.167				
C-POD location	s	re	7.68	28.51	< 0.001				
R-sq. (adj) = 0.0111; deviance explained = 27.0%; fREML = 96,124; scale est. = 1; *n* = 143,215									
Harbour porpoises									
Dolphin	s	cr	4.78	26.59	< 0.001	Intercept (before construction)	−3.72	−24.56	< 0.001
Sonar (vessel)	s	cr	2.82	141.53	< 0.001	During construction	0.29	4.78	< 0.001
Month (2016)	s	cr	10.87	786.88	< 0.001	After construction	0.58	2.45	0.015
Month (2017)	s	cr	10.52	226.45	< 0.001				
Month (2018)	s	cr	6.70	107.32	< 0.001				
Hour (before construction)	s	cc	4.54	4.52	< 0.001				
Hour (during construction)	s	cc	5.74	14.47	< 0.001				
Hour (after construction)	s	cc	5.11	31.13	< 0.001				
Month:hour	ti	cr:cc	33.69	3.44	< 0.001				
Current velocity and direction	te	cr:cc	10.22	25.81	< 0.001				
C-POD location	s	re	7.98	757.41	< 0.001				
R-sq. (adj) = 0.235; deviance explained = 30.2%; REML = 68,869; scale est. = 0.22415; *n* = 143,215									

Smooth types used were isotropic smooths (*s*), full tensor smooth interactions (*te*), and marginal tensor smooth interactions (*ti*). Spline types sued were cubic regression (*cr*), cyclic cubic regression (*cc*) and random effect (*re*). The effective degrees of freedom are displayed (*edf*)

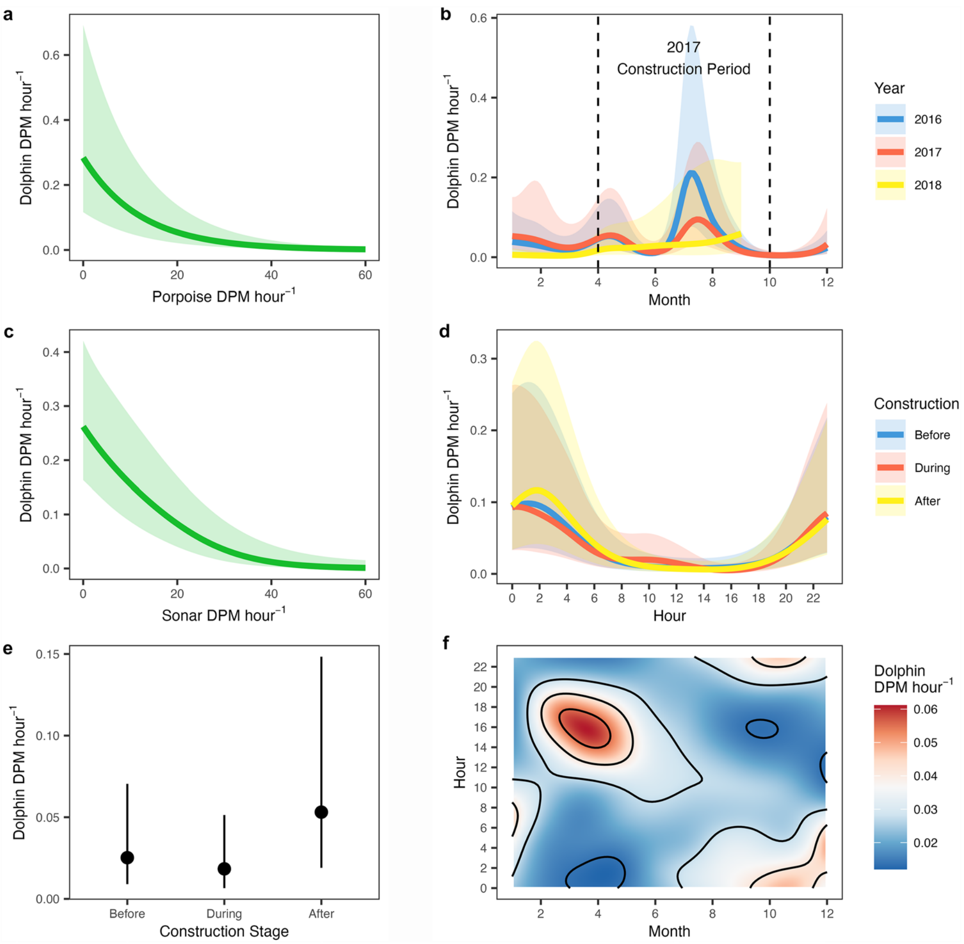


Fig. 2 Fitted partial effect relationships for the dolphin occurrence (DPM) Generalised Additive Mixed Model (GAMM). **a** The effect of harbour porpoise echolocation occurrence on the echolocation occurrence of dolphins. **b** Dolphin echolocation occurrence across months, with vertical lines demonstrating the bounds of the 2017 construction period for the gravity-based foundations. **c** The effect of vessel presence (DPM) on the echolocation of dolphins. **d** Dolphin echolocation occurrence across the diel cycle (24-h). **e** The hourly DPM of dolphins before, during and after construction of the array. **f** Dolphin diel echolocation activity across months. In all cases, the muted colours represent the bounds for the 95% confidence intervals for each smoothed covariate

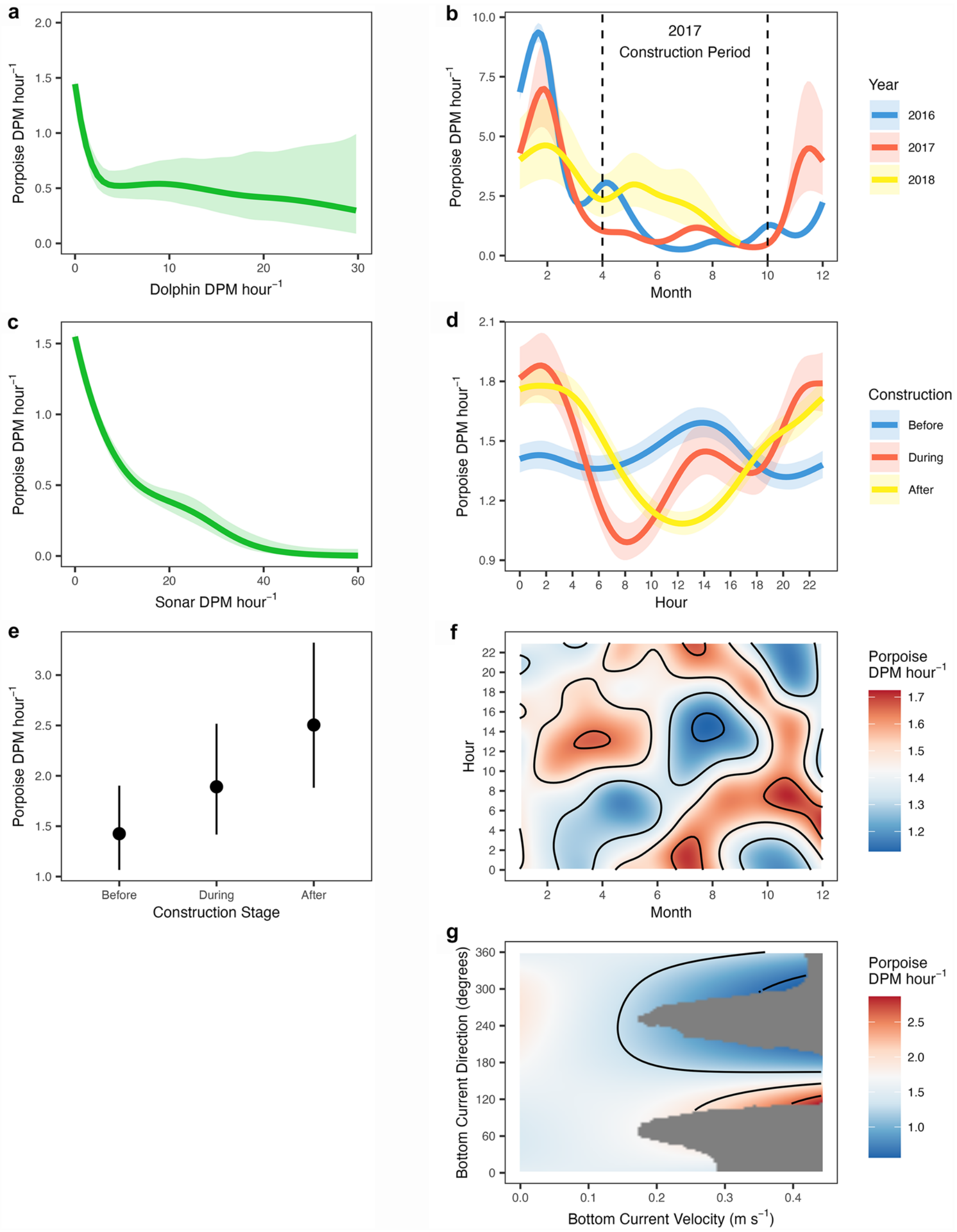
Dolphins

For dolphins, all variables, except tidal currents ($p = 0.167$) and construction phase (during construction: $p = 0.151$ and after construction: $p = 0.164$), included in the final model were significant ($p < 0.05$; Table 3). Overall, dolphin occurrence during and after construction were not significantly different to the occurrence before the construction phase (Table 3, Fig. 2e). Seasonal patterns in occurrence were similar in both 2016 and 2017, though the relative magnitude of variability in occurrence was lower in 2017, with highest occurrence in July–August with a secondary peak in April (Fig. 2b). Conversely, in 2018, the seasonal pattern of occurrence was less prominent, with no clear trend among months (Fig. 2b). A diel pattern in occurrence was found, with a decrease in occurrence during daylight hours in all construction phases (Fig. 2d). This diel pattern was also reflected in the combined marginal effects of Month and Hour. The level of occurrence during daylight hours, relative to hours of darkness, was highest in the Spring and lowest in the Autumn (Fig. 2f). Occurrence was also found to decrease with increasing levels of both harbour porpoise occurrence and vessel sonar occurrence (Table 3, Fig. 2a and c, respectively).

Harbour porpoise

All variables included within the final harbour porpoise model were found to be significant ($p < 0.05$; Table 3). Overall, harbour porpoise occurrence increased from 2016 to 2018 (Fig. 2e). Seasonal (monthly) patterns in occurrence were similar in all three years with a higher occurrence during winter compared to summer months although less pronounced in 2018 (Fig. 3b). A diel pattern in occurrence was found, with decreased occurrence during daylight hours in 2017 and 2018 during and after-construction (Fig. 3d). In contrast, in 2016 before construction, there was no clear diel pattern in occurrence except a slight increase in the afternoon (Fig. 3d). The diel pattern was also reflected in the combined marginal effects of Month and Hour (Fig. 3f). Occurrence was also found to decrease with increasing levels of both dolphin occurrence and sonar occurrence (Fig. 3a and c, respectively). Lastly, there was an effect of tidal currents on occurrence (Table 3, Fig. 3g). Increased levels of occurrence were found at periods of high current velocity

Fig. 3 Fitted partial effect relationships for the harbour porpoise occurrence (DPM) Generalised Additive Mixed Model (GAMM). **a** The effect of dolphin echolocation occurrence on the echolocation occurrence of harbour porpoises. **b** Harbour porpoise echolocation occurrence across months, with vertical lines demonstrating the bounds of the 2017 construction period for the gravity-based foundations. **c** The effect of vessel presence (DPM) on the echolocation of harbour porpoises. **d** Harbour porpoise echolocation occurrence across the diel cycle (24-h). **e** The hourly DPM of harbour porpoises before, during, and after construction of the array. **f** Harbour porpoise diel echolocation activity across months. **g** The effect of harbour porpoise hourly acoustic occurrence as influenced by tidal fluxes. In all cases, the muted colours represent the bounds for the 95% confidence intervals for each smoothed covariate. Confidence intervals for the impact of dolphin DPM increase dramatically beyond 30 DPM, the full plot for this variable is available in Online Resource 2



and current direction of ~ 100–150° (Fig. 3g), reflecting the ebb tidal phase in the area. Conversely, lowest levels of occurrence were found at periods of high current velocity and current direction of approximately 200–300° (Fig. 3g), reflecting the flood tidal phase. Little variation in occurrence was apparent during periods of low current velocity, where slack waters reflect low and high tidal phases.

Discussion

The use of gravity-base foundations for installation of offshore wind turbines offers a potentially low-impact alternative to traditional construction methods for wind turbines such as pile-driven monopile and/or jacket foundation installations (Teilmann and Carstensen 2012; Dähne et al. 2013; Brandt et al. 2018). This is supported by the results of this study that showed no evidence for negative long-term change in inter-annual occurrence for either harbour porpoise or dolphins during the wind turbine development off Blyth, Northumberland, UK. Further, harbour porpoise occurrence increased both during and after construction compared to before construction of the wind turbine array. For dolphins, there was an indication of a negative trend in occurrence during the construction phase followed by an after-construction increase in occurrence, although neither effect was statistically significant. Whilst the outcomes of this study are promising, there is need for further studies assessing potential effect on occurrence at different locations and for different species to determine whether the findings are broadly applicable. Data were not available in this study to investigate higher resolution effect of construction-related activities which may impact dolphin and harbour porpoise occurrence, such as sea floor preparation, type of vessels, cavitation noise and/or vessel behaviour, and disaggregation of their potential impacts should also be considered a future priority.

Whilst dolphins showed no significant change in occurrence between construction phases, harbour porpoise occurrence increased across the study period by 32% and 75% in the during- and after-construction period, respectively, compared to before the start of the construction. These results are in direct contrast to studies where pile-driving was used as the turbine installation method and where harbour porpoise occurrence declined during the construction period (Tougaard et al. 2005; Carstensen et al. 2006; Brandt et al. 2011). In some previous studies, harbour porpoise occurrence also remained low after construction at some locations (Teilmann and Carstensen 2012), whereas in others returned to before-construction levels or even increased beyond before-construction levels (Scheidat et al. 2011). Potential explanations have been offered for why occurrence of harbour porpoises might increase in some areas after construction, including the development of a "reef-effect" created by the introduction of hard substrates into the environment and decline in vessel activity including fisheries (Hoffmann et al. 2000; Langhamer 2012; Bergström et al. 2013). The introduction of new hard substrates (i.e. the turbines, gravity-based foundations and scour protections) to the otherwise soft-sediment might encourage prey-fish aggregation and show early signs of a reef-effect (Soldal et al. 2002; van Hal et al. 2017), but the post-construction time period is too short for a complex reef system to have formed. Further investigation is required to understand drivers behind the observed increased harbour porpoise occurrence after construction.

There was a distinct difference in the diel occurrence between dolphins and harbour porpoise. Dolphins were largely absent (or non-echolocating) during daylight hours whilst there was relatively little diel change in harbour porpoise occurrence before construction but more distinct diel patterns during and after the construction. Studies of dolphin acoustic activity have suggested that several species echolocate at a lower rate during daylight hours, possibly relating to patterns in foraging activity or increased use of visual cues during this period (Soldevilla et al. 2010a, 2010b; Wang et al. 2015). Previous studies of harbour porpoises off the west coast of Scotland (Carlström 2005), Dogger Bank (Todd et al. 2009), and off north-western Ireland (Todd et al. 2022) have demonstrated higher encounter rates at night containing higher click rates with minimum inter-click intervals of < 10 ms (ms), indicative of increased foraging activities. The findings of our study suggest that harbour porpoises are either echolocating less in the development site at night, possibly in response to the construction and operation of the wind turbines, or that they have shifted their diel use at the site, perhaps associated with increased foraging opportunities granted by a possible reef-effect or reduction in fishing activity.

Harbour porpoise occurrence was affected by tidal currents, but dolphins were not. Tidal effects on harbour porpoise have also been observed in other areas of the species distribution range (Johnston et al. 2005). The disparity in tidal current effects between species may reflect the difference in the main prey species between harbour porpoise and dolphins. Harbour porpoises generally target smaller schooling prey (e.g. Atlantic herring (*Clupea harengus*), European sprat (*Sprattus sprattus*), and sandeel (*Ammodytes* spp.)) (MacLeod et al. 2007) that are likely influenced by tidal currents. In contrast, dolphins generally target larger prey which may be less impacted by tidal currents, including Atlantic salmon (*Salmon salar*), cod (*Gadus morhua*), saithe (*Pollachius virens*), haddock (*Melanogrammus aeglefinus*) and whiting (*Merlangius merlangus*) (Santos et al. 2001). However, to date, there is limited information available on the prey preference and diet of bottlenose and white-beaked dolphins and harbour porpoise off the northeast coast of the United Kingdom to support if the difference between harbour porpoise and dolphins' diel behaviour is related to prey.

This study included a variable to account for vessel activity (*vessel sonar*) derived from the C-PODs and used as a proxy for vessel occurrence as a potential driver to harbour porpoise and dolphin occurrence. The sonar variable was significant in both the dolphin and harbour porpoise models and the effect size was substantial in both species, with around 8 min of sonar occurrence per hour leading to a 50% decline in harbour porpoise occurrence and around 13 min of sonar occurrence per hour leading to a 50% decline in dolphin occurrence. Generally, harbour porpoises are considered particularly sensitive to anthropogenic noise which may cause displacement or other behavioural adjustments when exposed to vessel presence (Hermannsen et al. 2014; Dyndo et al. 2015; Benhemma-Le Gall et al. 2021). Harbour porpoises have been displaced from important habitats due to increasing vessel traffic (Scheidat et al. 2011) and have shown changes in foraging activities (Pirotta et al. 2014).

Several behavioural changes associated with high levels of vessel traffic have also been noted including vigorous fluking, diving, interrupted foraging and cessations of echolocation activities (Wisniewska et al. 2018). High-speed, planing vessels were noted to elicit negative reactions in 75% of harbour porpoises observed in Swansea Bay (Oakley et al. 2017), likely because the received noise from planing vessels were louder (+ 13 dB re 1 µPa from the baseline measurements recorded in that study) compared to other non-planing vessels (+ 9 dB re 1 µPa from the baseline measurements) (Buckstaff 2004). Overall, impacts from vessel traffic have been demonstrated to influence harbour porpoises at distances over 1000 m from the original exposure site (Dyndo et al. 2015). Disturbance from sonar may increase energetic costs and negatively affect foraging success, having detrimental effect on the health of harbour porpoises due to their high metabolic needs (Wisniewska et al. 2016, 2018; Booth 2020). Despite this, the increase in harbour porpoise occurrence across this study suggests that construction and after-construction vessel activity around the BOD area did not result in any overall decline in area usage.

Potential impacts of dredging and other site preparation activities on harbour porpoise and dolphin occurrence are generally understudied (Todd et al. 2015) but has been shown to displace bottlenose dolphins from foraging habitats in other parts of the United Kingdom (Pirotta et al. 2013). Dredging is a necessary part of seabed preparation prior to the installation of gravity-base foundations (Peire et al. 2009; Coates et al. 2015) and may contribute to the indicated temporary decline in dolphin occurrence during the construction phase in this study.

In this study, we used C-POD detections of sonar activity as a proxy for vessel disturbance. Our analyses and its interpretation are, therefore, constrained by the detection range of the C-POD and may not capture high-resolution spatial–temporal patterns during the construction. C-POD sonar detections also do not allow for differentiation between vessel types, which may range from small recreational yachts to cable-laying vessels and large container vessels, and smaller vessels may not use echosounders on a constant basis or even lack them altogether. Therefore, the inclusion of other vessel monitoring data from, e.g. Vessel Monitoring Systems (VMS), Automatic Identification System (AIS) and other ways of monitoring of vessel numbers, types and activities, may provide a more comprehensive and higher resolution understanding of vessel activity, helping to better disaggregate the impacts of vessel activity on dolphins and harbour porpoise during wind turbine construction. One such alternative and/or complementary approach described by Lowes et al. (2019) uses a low-powered network of acoustic devices that monitor vessel occurrence and behaviour by identifying vessel propeller cavitation sound.

Extended temporal coverage, particularly before construction, would improve the reliability of construction effect assessment by increasing certainty in both the occurrence baseline and allowing analyses to account for natural levels of inter-annual variability, which may otherwise mask or exacerbate perceived construction effects. In addition, losses of C-PODs contributed to a significant reduction of data availability for this study (Online Resource 1), with two initial sites discontinued after repeated losses of C-PODs and other sites impacted variably by sporadic C-POD losses. Whilst more frequent maintenance might reduce data losses, this undermines the cost effectiveness of archival PAM systems. One solution would be the development of affordable PAM systems capable of transmitting the data to a nearby receiver, rather than archivally storing the data (Berggren et al. 2019; Van Parijs et al. 2021; Sherlock et al. 2022). Lastly, as with many other archival PAM systems, the C-POD and the associated analysis software do not currently allow differentiation between different dolphin species and in the case of the current study common bottlenose dolphins and white-beaked dolphins. This may mean that species-specific area uses and responses to construction activity using gravity-based foundations may be partly or wholly obscured. Efforts to enable differentiation between dolphin species will, therefore, be key to improving similar studies in the future.

Conclusion

Our findings indicate that wind turbine installation using gravity-base foundations had no long-term effects on the occurrence of dolphins or harbour porpoises in the vicinity of the wind turbine locations. However, there was indication of a short-term reduction in dolphin occurrence during construction and a diel shift in harbour porpoise occurrence during and after construction that warrant further study. Given these results, gravity-base foundations may represent an offshore construction methodology that is less impactful to toothed whales than traditional pile-driven turbine foundations. However, impacts may vary by area and/or species. Therefore, additional studies are recommended during future offshore construction using gravity-base foundations to determine if the patterns and responses observed in this study are representative of the impacts of this foundation type. Future developers and permitting agencies should continue to explore the potential impacts of novel offshore renewable technologies in conjunction with well-designed, spatially and temporally representative monitoring and assessment strategies.

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Author contributions All the authors contributed to the design of the study, methodology, writing and review of the manuscript. KP and AT were responsible for formal analysis, data curation and data visualisation. PB and AT were responsible for the conceptualisation, funding acquisition, and administration of the project. All the authors drafted, edited and approved the final manuscript.

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Data availability The data used in this study are available upon request from the authors. In addition, requests for the data can also be made to the Crown Estate, who hold the data in a repository.

Declarations

Conflict of interest All the authors declare that they have no conflict of interest related to this publication. The Corresponding Author (PB) was the recipient of the funding from EDF Renewables, UK but affirms that this did not affect the implementation of the study, the analysis, the interpretation of the results, the conclusions of the manuscript, or the decision to publish. KP works for the National Oceanic and Atmospheric Administration's National Marine Fisheries Service performing offshore wind permitting tasks but affirms that this affiliation did not influence the interpretation of the results, the conclusions of the manuscript, or the decision to publish.

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