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Acoustic ecology of harbour porpoise (*Phocoena phocoena*) between two U.S. offshore wind energy areas

A. K. Holdman [1,*], N. Tregenza[2], S. M. Van Parijs [3], and A. I. DeAngelis [3]

[1]Integrated Statistics, under contract to the Northeast Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration (NOAA), Woods Hole, MA 02543, USA
[2]Chelonia Limited , Mousehole TR19 6PH, Cornwall, UK
[3]Northeast Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Association (NOAA), Woods Hole , MA05243, USA

*Corresponding author: Tel: +(508) 233-8009; Fax: +(508) 495-2232; e-mail: amanda.holdman@noaa.gov

Offshore wind energy is set to develop rapidly in waters off the east coast of the United States. There is considerable overlap between areas proposed for offshore wind development and harbour porpoise habitats in the Gulf of Maine (GOM) and Southern New England waters. Baseline data on the occurrence and foraging activity of porpoises was collected using 10 echolocation-click detectors (F-PODs) from 2020 to 2022. Porpoises were present year-round in the GOM with peak detections in the summer and fall. In line with previous reported distribution patterns, porpoise occurrence in Southern New England was high in fall, winter and spring, but porpoises were largely absent in the summer. One site in the GOM, Mount Desert Rock (MDR), was an anomaly as porpoise detections here were highest in the winter. On average, foraging was identified in 29% of all porpoise detections, with the most foraging occurring at MDR (53%). Results from generalized additive models suggest that time of year, hour of day, lunar illumination, and temperature are significant contributors to porpoise presence and/or foraging effort. European studies show that harbour porpoises exhibit behavioural changes, disruption of foraging and displacement due to wind energy development. Therefore, early identification of areas of importance, mitigating impacts, and monitoring changes is essential for the protection of this species in US waters.

Keywords: baseline data, distribution, foraging, generalized additive models, harbour porpoise, offshore wind energy area, passive acoustic monitoring.

Introduction

A growing demand for sustainable energy has led to a rapid increase in development of offshore wind energy areas (WEA) worldwide. The United States is no exception and aspires to add nearly 30 gigawatts of offshore wind energy by 2030. Incidentally, the Bureau of Ocean Management (BOEM) has issued or is reviewing lease requests for commercial-scale wind energy development throughout much of the north-western Atlantic Ocean (Office of the Press Secretary, 2022). Offshore WEAs are often constructed in shallow environments with high biodiversity and cover large areas. As such, WEAs frequently coincide with biologically important areas and critical habitats for cetaceans (e.g. O'Brien *et al.*, 2022; Harrison *et al.*, 2023). Impacts from wind development on cetaceans may be direct (affect the animals themselves) or indirect (affect the animals habitat or prey) and can be negative (collision/noise effects) or positive (increased foraging opportunity as a result of artificial reef properties) (Inger *et al.*, 2009; Galparsoro *et al.*, 2022). The intensity of these effects can also be expected to differ at each WEA depending on location, the type of development, the species present in the area, and the importance of the habitat to the species (Schuster *et al.*, 2015; Galparsoro *et al.*, 2022). For instance, developments placed in or adjacent to sensitive areas for cetaceans such as those used for breeding, nursing, feeding, or migration will likely have greater repercussions than developments located away from these critical areas (Galparsoro *et al.*, 2022). Moreover, large arrays of wind turbines can be expected to have greater effects than that of a single device, and neighbouring developments may have combined impacts to cetaceans (Inger *et al.*, 2009). Numerous studies have addressed the range of impacts to marine mammals, and provided recommendations for evaluating and mitigating those impacts (e.g. Inger *et al.*, 2009; Bailey *et al.*, 2014; Van Parijs *et al.*, 2021).

Offshore wind energy has grown substantially in southern New England waters since the first small-scale (five-turbine 30 MW) wind energy array was constructed at Block Island Wind Farm in 2016. Since then, eight other areas have been leased across Rhode Island and Massachusetts, with Vineyard Wind (62 turbine, 800 MW) and South Fork Wind (12 turbine, 132 MW) scheduled to be the first commercial-scale wind farms in the United States. Nearby areas, such as the Gulf of Maine (GOM), are also targeted for offshore wind energy development and could potentially host up to 860 (10GW) floating offshore wind turbines. As a result, there is an immediate need to provide managers and stakeholders with local and regional population level information on species of concern in these completed, ongoing, and planned WEA.

Sensitivity of harbour porpoises (*Phocoena phocoena*) to underwater noise and entanglement is well established in the United States (NMFS, 2022a), generating concerns for spatial overlap between wind energy developments and the preferred coastal habitat of this small cetacean. Harbour porpoises have been the focus of many studies on the effects of offshore wind construction in Europe (e.g. Schuster *et al.*, 2015; Brandt *et al.*, 2018) and have been found to be negatively affected during construction and operation (Gilles *et al.*, 2009; Teilmann and Carstensen, 2012). Consequently, harbour por-

poises have been identified as a focal species in regards to assessing the risks of WEA development in the United States (Southall *et al.*, 2021). If close enough to loud sound sources, harbour porpoises can suffer temporary or even permanent hearing loss (Lucke *et al.*, 2009; Kastelein *et al.*, 2012). Other effects, including masking and behavioural responses, occur at much larger distances (Tougaard *et al.*, 2009). Harbour porpoise displacement has been well documented in relation to activities associated with wind energy including pile driving during construction (Dähne *et al.*, 2013; Benhemma-Le Gall *et al.*, 2021), turbines during operation (Koschinski *et al.*, 2003), and vessel noise (Benhemma-Le Gall *et al.*, 2021) during maintenance. While all phases of wind energy development may cause acoustic disturbance, the construction phase is the most intensive and likely to cause the most displacement. Although, this displacement appears to be temporary. Several studies have found that harbour porpoises return to a wind farm area once construction has ceased and the farm is operational, but this has ranged from a few hours (Tougaard *et al.*, 2006) to several days (Brandt *et al.*, 2011), and in a couple instances, a few years (Teilmann and Carstensen, 2012).

Harbour porpoises are small-bodied and must feed regularly in order to fulfil their daily metabolic requirements (Rojano-Doñate *et al.*, 2018; Kastelein *et al.*, 2019). As a result, porpoises cannot stray far from areas containing reliable prey resources and individuals can die from starvation in less than a week if they do not find adequate prey (MacLeod *et al.*, 2007). Disturbance of critical behaviours such as feeding, mating and nursing, as well as displacement from potentially important habitat could lead to a reduction in fitness of individual animals, and ultimately may result in reduced fitness of the population (Pirotta *et al.*, 2018; Kastelein *et al.*, 2019). Small or moderate displacement of porpoises for weeks or months can lead to adverse consequences, with the scale of impact likely to depend on the duration of the displacement, and the quality of alternative habitat.

It should be noted, however, that porpoises do not have to be displaced to experience reduced foraging efficiency and mating opportunities. Exposure to impulsive sounds and vessels can result in altered behaviour (e.g. calling rates, feeding, breathing, movements) that subsequently may reduce food or mate-finding abilities or increase chronic stress (reducing health and fecundity) (Kastelein *et al.*, 2013; Dyndo *et al.*, 2015; Wisniewska *et al.*, 2018). Individuals have to make trade-offs between using energy to leave the area or remain in an exposed area and tolerate higher levels of disturbance (Frid and Dill, 2002; Pirotta *et al.*, 2014).

Offshore wind farm studies should be independent, and not extrapolate results from one area to the next, especially from Europe to US Atlantic waters. While it is important to build on what has been learned so far, the physical environment, impact ranges, and durations of each wind farm installation will be different from each other and from Europe. A thorough evaluation of the effects will depend on the availability of population-specific data on porpoise occurrence and foraging collected prior to development during their normal, baseline activities, against which any changes from future monitoring can be compared.

PODs (Chelonia Ltd, 2022), have been widely used to detect harbour porpoise echolocation clicks both independently (e.g. SAMBAH project, Koblitz *et al.*, 2014; Carlén *et al.*, 2018) and as a complement to visual methods (e.g. Williamson *et al.*, 2017). Data from PODs are often used to describe fine-

scale patterns in distribution, behaviour, and relative abundance of harbour porpoise (e.g. Benjamins *et al.*, 2017; Todd *et al.*, 2022; Williamson *et al.*, 2022) as well as to assess effects from wind farm construction (Tougaard *et al.*, 2009; Brandt *et al.*, 2011). Harbour porpoises exclusively rely on echolocation, with differences in their inter-click-intervals (ICIs) signifying different behaviours (e.g. search and capture in foraging versus communication, Villadsgaard *et al.*, 2007; Clausen *et al.*, 2011). In the final stages of a prey-capture attempt, known as a buzz, harbour porpoise ICIs may be reduced to intervals as low as 2.5 to 15 ms (Koblitz *et al.*, 2012). Consequently, the number of buzzes recorded on loggers has been used as an indicator of foraging frequency (e.g. Miller *et al.*, 2004).

In order to understand the baseline spatial and temporal variation in harbour porpoise occurrence and foraging patterns prior to wind energy installation, data from F-PODs at 10 sites were analysed from inshore GOM to Southern New England waters over a two-year period from 2022–2022.

Materials and methods

Data collection

F-PODs (successor to C-PODs) were deployed at 10 sites within two regions: six sites along the coastal GOM and four sites surrounding or within the Southern New England (SNE) wind energy area (Figure 1). Starting in November 2020, two instruments were deployed in SNE, and eight additional stations were deployed over the next year (Figure 1, Table 1, Figure S1). The overall recording period was from 15 November 2020 to 27 October 2022. Each mooring contained a single F-POD, which continuously monitors the 17–210 kHz frequency range for possible cetacean echolocation clicks and records the time of occurrence, duration, frequency, intensity, bandwidth, and several points on the waveform envelope of each click. F-PODs do not record the raw sound, only a subset of informative parameters of each click, hereby conserving battery power and memory storage. F-PODs are capable of detecting porpoise clicks within an omnidirectional range of up to 400 m (Chelonia Ltd). F-POD moorings were bottom-anchored with the logger positioned ~4 m from the seafloor. Surface lines and buoys were not used in order to keep the equipment inconspicuous and minimise interference with fisheries as well as North Atlantic right whales. Instead, an acoustic release was used, which upon command, detaches the mooring from the anchor so that it may be recovered at the surface. Approximately every 5 months, F-PODs were recovered, the batteries and memory cards were replaced, and the F-POD was redeployed on-site. The water depth across the deployment locations ranged from 32 to 107 m and the recording effort among the 10 recorders varied due to delayed servicing from weather events and equipment loss due to trawling (Table 1).

F-POD data processing

Every time the F-PODs were recovered, acoustic data were downloaded and processed for click detections using the manufacturer's software, FPOD.exe (Chelonia Ltd, 2022) and accompanying classifier, KERNO-F v1.0. Narrow band high frequency (NBHF) click trains of high and moderate quality were identified and exported. The quality classes express the likelihood of the train having come from a true source of click trains rather than being a chance coincidence of similar clicks
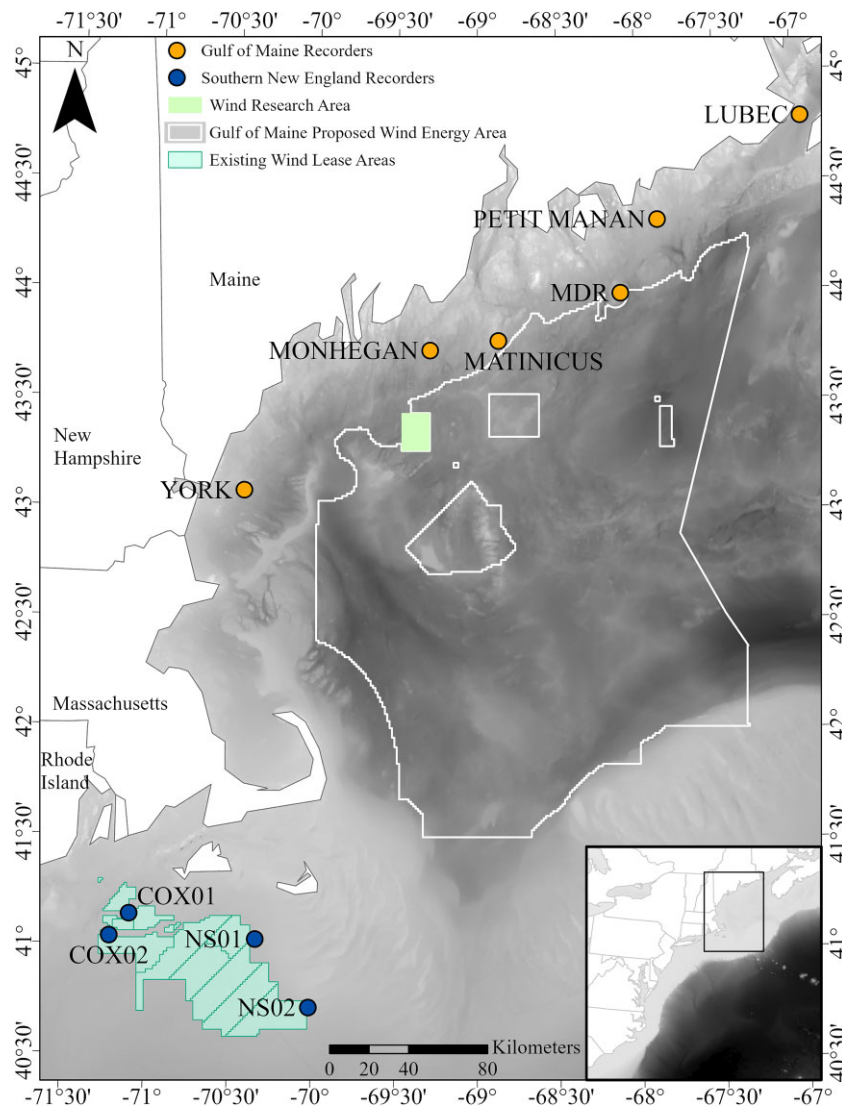
Figure 1. Map of study area showing the locations of the F-POD recorders. Each region defined in the study is shown as a different colour, where orange circles represent the recorders located in the GOM region, and blue circles represent the recorders located in the Southern New England region. Site name of each recorder is shown next to each recorder location. Current WEA and the smaller lease areas within those WEA are shown in a teal-shaded area, the proposed area of offshore wind is shown as a white outline. The Maine wind research area is shown as a green rectangle. The bathymetry of the study area is shown in greyscale where darker greys represent deeper areas. Bathymetry layer provided by GEBCO Compilation Group (2022) GEBCO_2022 Grid (doi:10.5285/e0f0bb80-ab44-2739-e053-6c86abc0289c). The inset shows the location of the study area in relation to the East Coast of the United States.

Table 1. F-POD deployment site details: F-POD sites (site ID), recording location (latitude and longitude), water depth (FPODs were suspended 4 meters from sea floor), first date of data collection (start date), last date of data collection (end date) and the total number of complete days for each site.

Site ID	Latitude (°)	Longitude (°)	Water depth (m)	Start date	End date	Total days
Lubec	44.7824	− 66.9378	91	19 July 2021	07 July 2022	353
Petit Manan	44.3182	− 67.8590	61	22 July 2021	07 September 2022	412
Mount Desert Rock	43.9851	− 68.0975	107	26 August 2021	07 September 2022	377
Matinicus	43.7673	− 68.8669	63	27 August 2021	27 March 2022	212
Monhegan	43.7242	− 69.2962	61	27 August 2021	23 August 2022	361
York	43.0803	− 70.4484	80	21 August 2021	20 September 2022	395
NS01	41.0334	− 70.3413	38	13 October 2021	29 May 2022	228
NS02	40.7241	− 70.0170	43	14 October 2021	27 October 2022	378
COX01	41.1418	− 70.1031	32	15 November 2020	21 August 2022	644
COX02	41.0394	− 71.2189	41	15 November 2020	22 October 2022	706

to form a sequence resembling a true train. Successively lower quality classes give a higher risk of false positives and a higher sensitivity. In accordance with other studies, click trains classified into the two highest quality classes, high and moderate, were selected and used in our analysis, while low and possible echo click trains were disregarded (e.g. Wingfield *et al.*, 2017). Classified click train data were exported from the FPOD.exe software as porpoise positive minutes (PPMs) in a binary output; i.e. either no click train or at least one click train (containing at least five consecutive clicks) within a given minute. A visual validation of automatically identified click trains was performed on 100 randomly selected PPMs with click trains. Using the display tools in FPOD.exe, porpoise detections were verified for correct species classification through visual screening following procedures specified by Chelonia Ltd (2022) and parameters that meet the known acoustic characteristics for harbour porpoise (e.g. Gallus *et al.*, 2012). Detections of possible porpoise origin were rejected and thus classified as a false positive when (1) ICI did not show the variation in click pattern seen in echolocation click trains, (2) variation between successive clicks was incoherent, and (3) another source of the detected sound could be identified (boat engine or sonar, ambient noise) as the source of the classified click train. This visual screening resulted in a <1% false positive rate based on a total of 3 015 PPMs validated of a total of 231 515 PPMs classified throughout the study. To compare porpoise presence across the study sites, the % detection was calculated (PPM/recording minutes) for each deployment location. To examine the seasonal distribution of porpoise, we calculated the % presence (PPM/recording minutes) for each month at both the site and regional level. Only minutes with full 60 second coverage were included in the analysis, i.e. the first and last incomplete minute of a recording period were discarded.

Identifying foraging events

In accordance with previous studies, we used the detection of sequences with a median ICI shorter than 10 ms to identify a foraging buzz (Carlstrom, 2005; Todd *et al.*, 2009; Verfuß *et al.*, 2009). Minutes with potential foraging buzzes were marked as present and exported as buzz-positive minutes (BPM). To examine the amount of time harbour porpoises spent foraging while at a survey site, we computed the percentage of BPM to PPM for all locations.

Generalized additive modelling of clicks

Patterns in porpoise occurrence (PPM) and foraging (BPM) were further investigated in relation to seasonal, diel, and lunar cycles, as well as temperature using generalized additive models (GAMs). For each region, two different models were fitted to the data: one investigating the occurrence of harbour porpoise and the other investigating porpoise foraging activity. We originally planned to have two regions (GOM and SNE); however, upon preliminary analysis, a third region was created (see "results" section below). For the occurrence model, PPMs were binned into hourly presence to create a binomial response variable representing the presence or absence of harbour porpoise within the hour. For the foraging model, a subset of data was created that consisted of only harbour porpoise detection positive hours. Within this subset of data, the binomial presence or absence of foraging buzzes were categorised to be used as the response variable in the foraging models. Since the foraging models aim at estimating the likelihood that a porpoise present at the F-POD is feeding, hours

in which no porpoise clicks were detected were excluded from this analysis. Binomial hourly response variables were chosen over counts to simplify interpretation of the vast data set and to reduce effects of autocorrelation. Only hours with full 60 minute coverage were included in the GAM. Further details of the GAM modelling approach and results are provided in the Supplementary Material, available at ICESJMS.

Results

A total of 3 895 days of data were recorded across the 10 monitoring sites, corresponding to over 5.6 million minutes of acoustic data used for analysis (Table 1). Acoustic monitoring efforts ranged from 212 days at Matinicus to 689 days at COX02 (Table 1, Figure S1). Three sites recorded continuously for the entire duration, while at two sites, Matinicus and NS01, recordings were cut short due to equipment loss (Figure S1). At the remaining sites, gaps in data collection occurred between deployments due to weather and other logistical constraints. These gaps ranged from a few weeks to a couple of months depending on the F-POD battery life and servicing schedule.

Patterns of occurrence and foraging

Harbour porpoise presence and foraging behaviour were detected at all monitoring locations. There was substantial variability in the number of PPMs across locations. The proportion of PPMs to total monitoring minutes per site ranged from 12% at Mount Desert Rock (MDR) to <1% at COX01 and COX02 (Figure 2a). BPMs followed a similar pattern as PPMs, with the highest foraging BPMs at MDR (53%, Figure 2b). Foraging rates at all other sites were fairly similar (20–32%, Figure 2b), even at sites with relatively low overall detection of porpoises (i.e. COX01 and COX02, <1%, Figure 2a).

Porpoises were detected year-round in the GOM with peak detections from August to November (Figure 3a and b). One site in the GOM, MDR, was a major outlier with unusually high activity from January through May (winter/spring) and unusually low activity from August to November (late summer/fall) compared to the other GOM sites (Figure 3b). As a result, we treated MDR as a separate "region" for subsequent analyses since the PPMs represented the inverse of all other GOM sites (Figure 3b).

Harbour porpoises in SNE displayed strong seasonal patterns that were similar to MDR—highest detection in colder months. Porpoise clicks were present from the last week of October to the beginning of July, with the highest % detection from January through April (Figure 3b). No porpoises were acoustically detected during July and August for either sampling year in SNE (Figure 3a).

GAM modelling

Details of the GAM models for each region are available in the supplementary Material. For each of the three regions, the GAM that best described the occurrence of harbour porpoises was the full model that included temperature and all three temporal effects (month, diel hour, and lunar illumination) with the random effect of deployment location (site):

$$\text{Occurrence} \sim s(\text{Month by} = \text{Site})$$
$$+ s(\text{Diel hour by} = \text{Site}) + s(\text{Lunar Illumination by} = \text{Site})$$
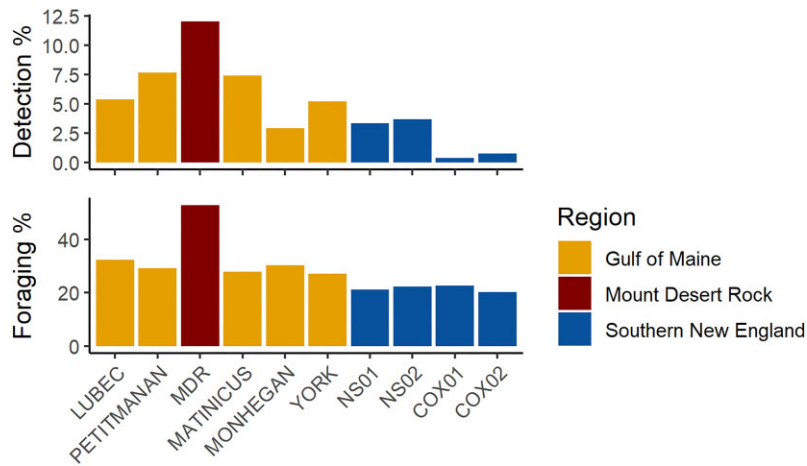$$+ s(\text{Temperature by} = \text{Site}) + \text{Site(re)}.$$

Figure 2. Percent of porpoise detection (top) shown as porpoise positive minutes (PPMs/recording minutes) for each "region" in the study. Percent of minutes that contained an interclick interval (ICI) < 10 ms, thus classified as foraging (bottom).
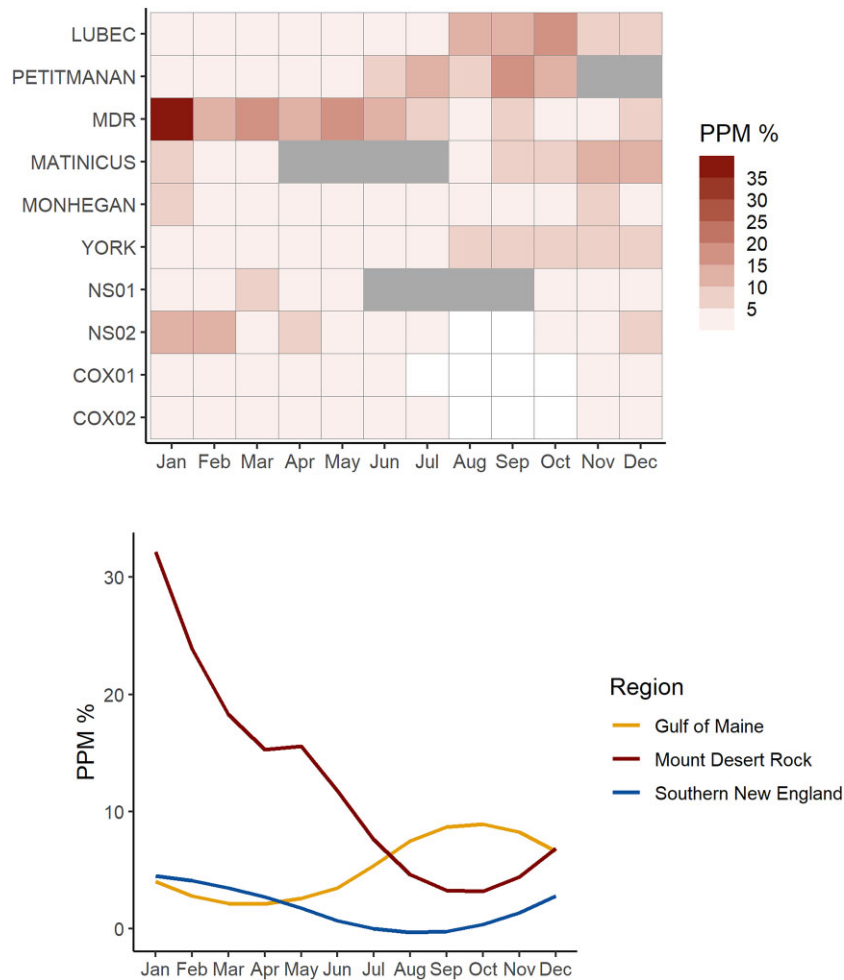

Figure 3. Monthly acoustic presence of harbour porpoise recorded at the site level (a) and the regional level (b) from November 2020 to November 2022. The % detection of porpoises have been standardized for recording effort for each month. In figure a, white represents acoustic absence while grey represents a lack of data.

This model explained 16.9% of the deviance in the GOM, 17.9% of the deviance at MDR and 33.6% of the deviance in hourly occurrence at SNE (Table 2). Overall, patterns observed in the GOM region were heterogeneous and displayed significant variability between sites, while patterns observed in the SNE WEA were homogenous, with little to no variability between sites. Temperature was retained in all final presence models (for all regions and all sites) as a significant predictor

Table 2. Predictor variables in generalized additive models (GAMs) of harbour porpoise echolocation activity and their significance, with deviance explained of the entire model. Light grey is significant at the 0.05 probability level, medium grey is significant at the 0.01 probability level, and dark grey is significant at the 0.001 probability level.

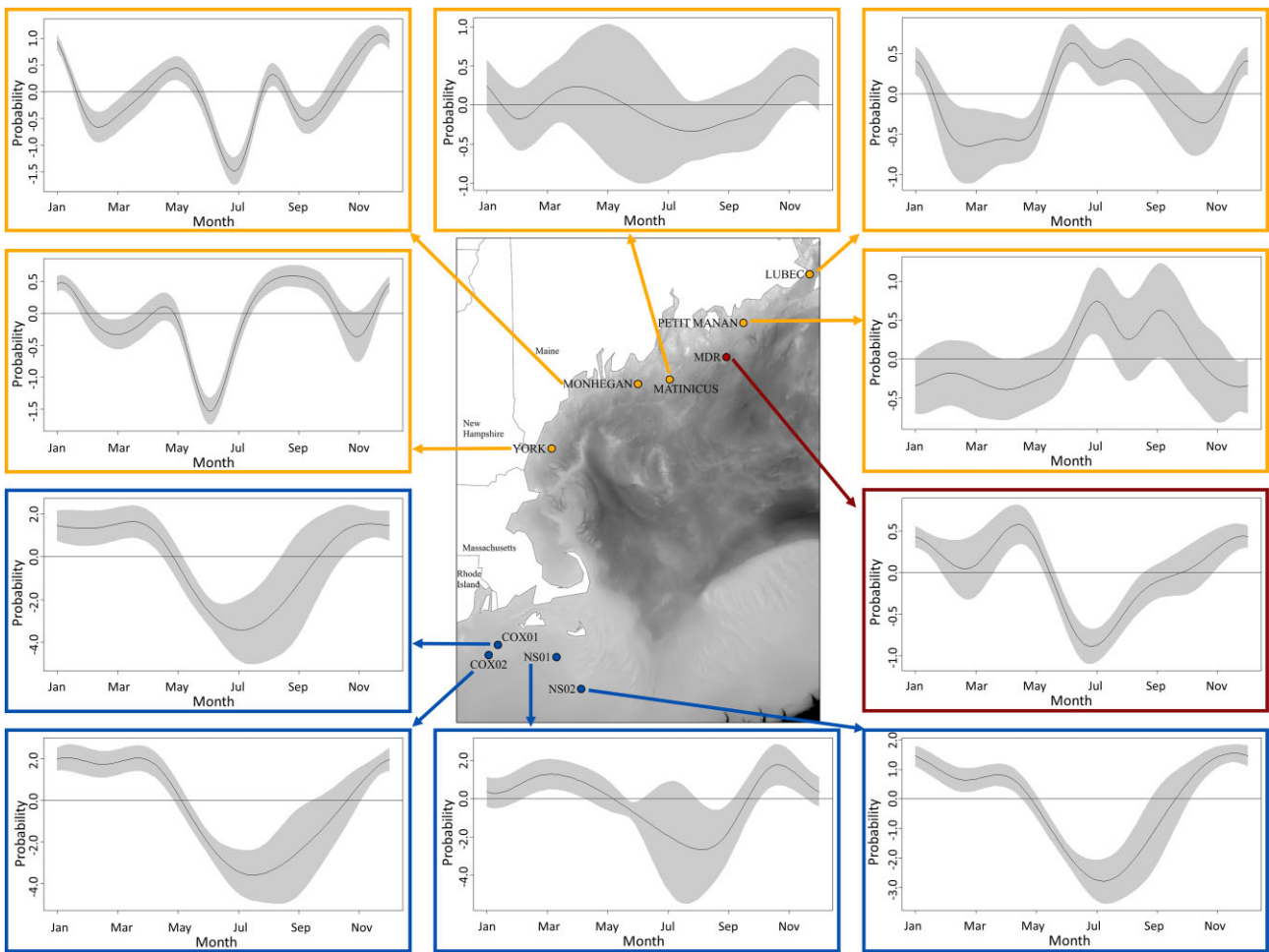| Region	Model	Deviance explained	Site	Month	Hour	Moon illumination	Temperature
GOM	Occurrence	16.90%	Lubec		-		
			Petit Manan				
			Matinicus				
			Monhegan				
			York				
	Foraging	4.83%	Lubec		-		
			Petit Manan				
			Matinicus	-		-	
			Monhegan		-	-	
			York			-	
MDR	Occurrence	17.90%	MDR				
	Foraging	3.64%	MDR			-	
SNE	Occurrence	33.60%	COX01			-	
			COX02		-		
			NS01				
			NS02				
	Foraging	5.50%	COX01	NA		-	
			COX02	NA		-	
			NS01	NA		-	-
			NS02	NA		-	-

Figure 4. GAM showing the smoothed effect of month on the hourly presence or absence of harbor porpoise echolocation clicks across the 10 monitoring locations. Recorders in the GOM are shown as yellow circles, with MDR shown in a different colour (red) as its pattern was different from the rest of the GOM. Southern New England recorders are shown in blue. The shaded region in each graph represents the 95% confidence band for a given smooth.

for harbour porpoise occurrence (Table 2). Water temperature during the survey period ranged from 3°C to 31°C, but no porpoises were detected when water temperatures were warmer than 16°C. The influence of season (i.e., month) on the number of porpoises present was significant for all sites except Matinicus, but it differed among locations (Figure 4). In the GOM, Lubec and Petit Manan showed a general increase during the summer through fall months (June to October), while at Monhegan and York, presence peaked later in the year, between Octobers to January. In SNE, harbour porpoises were present October through July, but absent in the summer. Diel and lunar illumination had varying levels of influence for presence at different regions and sites (see Figures S2–S4 for full occurrence modelling results).

Within hours of porpoise presence, foraging click trains (i.e. buzzes) were detected in 59% of those hours at GOM, 77% at MDR, and 45% of those hours at SNE. The best GAM for describing porpoise foraging in the GOM was the full model, while reduced models were more parsimonious at MDR and SNE (see Figures S5–S7 for foraging modelling results).

Discussion

The observed seasonal pattern of harbour porpoise occurrence in this study is consistent with prior information on the general distribution of the GOM/Bay of Fundy stock (Wingfield et al., 2017; NMFS, 2021). This population moves between their summer (July–September) habitat in the northern GOM and southern Bay of Fundy to as far south as North Carolina in the winter (January–March). During spring (April–June) and fall (October–December), porpoises from this population (and perhaps other populations, Rosel et al., 1999) are widely dispersed with lower densities in the north and south. In this study, the exception to this general pattern was MDR, where a notably high number of porpoises were recorded during winter (particularly January but largely present until June), when porpoises are thought to be dispersed (Hayes et al., 2019).

In addition to the opposing seasonal pattern observed at MDR, foraging was exceptionally high at this site with buzzes detected in 53% of all PPMs Areas where currents meet, like headlands and reefs with steep slopes or areas with strong tidal forces, can create large water movements that result in aggregations of prey that attract marine top predators (Johnston et al., 2005; Pierpoint, 2008). A similar phenomenon may be occurring at MDR. The coastal current in the eastern GOM has two cores, an offshore and a nearshore core. The two cores are merged as they flow downstream but then split into two branches east of MDR where the nearshore branch follows the coast and the offshore branch turns southward to recirculate in the eastern GOM (Li et al., 2021). The offshore core has a large current velocity in winter and early spring, which is when porpoise presence at MDR is highest. This area of high currents and upwelling likely creates zones of high biological productivity (Scott et al., 2010) around MDR during this time, which in turn could attract porpoises. Furthermore, there may be a greater incentive to occupy areas where prey species are abundant (Gilles et al., 2009). A local area to forage in the winter within the GOM, may be particularly beneficial for females, who spend most of the year lactating and pregnant in this region (Read and Hohn, 1995). Calves would also benefit, as they undergo major growth during their first year of life to build the necessary blubber stores required to handle environmental stressors (Stepien et al., 2023).

Porpoises are not only known to vary their distribution and movements in response to dynamic biological and physical variables (e.g. van Beest et al., 2018) but also in response to cycles in abiotic factors that result in regular and recurrent variations in prey availability (e.g. Sveegaard, 2011). In the GOM (including MDR), different patterns in presence and foraging in relation to seasonal, diel, and lunar were observed for each site, making biological interpretation of such patterns difficult. The broad geographic distribution of recorders in comparison to SNE may explain this difference in variability, or the complex geography and innately dynamic oceanography in the GOM could be driving this variability. A seasonal effect was seen at most locations, but this effect differed from one location to another. Porpoise presence peaked at the northern GOM sites (Lubec/Petit Manan) in the summer (September and October), while sites located more in the lower and central GOM (Matinicus, Monhegan, and York) displayed an increase in detections in first in May and then again in November/December. These central sites may serve as more of a transit route between the northern GOM and the mid-Atlantic and thus show a weaker pattern in seasonality than the northern sites. Porpoise occurrence and foraging varied on diel scales as well. At most sites, porpoises showed a preference for both presence and foraging during the night. However, at Petit Manan, daylight hours were preferred. Lunar illumination followed a similar trajectory and influenced porpoise occurrence at all locations, but each site displayed a different pattern, with no trends discernible. For porpoise foraging, however, Petit Manan had an increase of buzzes at new moons, and Lubec had an increase of buzzes at both new and full moons. These sites are located closer to the Bay of Fundy, which has the strongest tides in the world (Desplanque and Mossman, 2001) and thus lunar illumination could be serving as a proxy for the tidal phase, which has been known to influence porpoise distribution near these locations (Johnston et al., 2005) and elsewhere (Pierpoint, 2008; Benjamins et al., 2016). When considering all sites together in the GOM, such variability suggests optimization in distribution and foraging behaviour by porpoises in relation to temporally and spatially changing environmental and biological conditions.

At SNE, all sites displayed similar patterns in porpoise presence and foraging. A significantly higher percentage of PPMs and BPMs were detected at night than during the day in all sites. This pattern is widely observed in several porpoise populations around the world (e.g. Carlstrom, 2005; Todd et al., 2009; Williamson et al., 2017) and has been suggested to reflect higher prey availability at night (Scheidat et al., 2008). However, an increase in detections at night is not observed everywhere and differences in habitat (i.e. bottom type and associated foraging strategies) may offer an explanation as to why it is observed in many but not all habitats (Williamson et al., 2017; Williamson et al., 2022).

Alternatively, controlled studies suggest that increased echolocation at night could be in response to changing light availability rather than prey activity (Osiecka et al., 2020). In the present study, lunar illumination also had a distinct effect on porpoise distribution (but not foraging) at SNE. During times of increased illumination, porpoise echolocation was decreased; a phenomenon known as lunar phobia. Only a few studies have investigated the relationship between the moon and porpoise activity (de Boer et al., 2014; Wingfield et al.,

2017b; Osiecka *et al.*, 2020; Brennecke *et al.*, 2021; Stedt *et al.*, 2023) and none of them have observed the pattern identified in this study. Decreased echolocation activity during increased lunar illumination has, however, been observed in other odontocetes such as common dolphins (Simonis *et al.*, 2017). As there seems to be no effect of lunar illumination on the amount of produced foraging buzzes in this study, this could be another instance where lunar illumination also improves the ability of porpoises to use visual cues as a complement to echolocation (e.g. navigation, communication) (Osiecka *et al.*, 2020; Bakkeren *et al.*, 2023).

Echolocating less during periods of daylight or bright moonlight could also aid as a strategy to reduce predation risk similar to beaked whales and dusky dolphins, which reduce their foraging time to initiate anti-predator avoidance behaviours. (e.g. Baird *et al.*, 2008; Srinivasan & Markowitz, 2010; Barlow *et al.*, 2020). Predator avoidance has been suggested to be the cause for porpoises and other narrow-band high-frequency species to abandon low-frequency communication such as whistles and rely solely on the use of high-frequency echolocation (Galatius *et al.*, 2019). It is possible that porpoises limit their echolocation during certain conditions to avoid predation as well. Furthermore, bottlenose dolphins (*Tursiops truncatus*) are known to kill harbour porpoises in California and the United Kingdom (Cotter *et al.*, 2012., Jepson & Baker, 1998). In response, harbour porpoises have been found to change their distribution to avoid areas and times that bottlenose dolphins are present (Williamson *et al.*, 2022). The strong negative relationship to increased illumination may also reflect additional pressure to avoid bottlenose dolphins, but this interspecies dynamic has not been investigated in our study area.

While the percentage of deviance explained for some models was relatively low, particularly for foraging (min = 3.8%), there was sufficient statistical power to identify trends in presence and foraging patterns. Results from these models can provide marine resource managers with the information they need to select locations or temporal periods for installation that minimise harm to porpoises. It is not unusual for temporal models of cetacean occurrence and behaviour to only explain a relatively small amount of the deviance (Holdman *et al.*, 2019; Palmer *et al.*, 2022; Todd *et al.*, 2022). It is almost certain that porpoise presence and foraging in this region are influenced by oceanographic, and environmental drivers that were not considered in this study (e.g. tides). Temperature was found to be a highly significant driver of porpoise presence. Including other dynamic habitat variables (e.g. salinity, chlorophyll, and upwelling fronts) and environmental pressures (e.g. vessel or bottlenose dolphin presence) in future modelling efforts, could further unveil patterns of porpoise distribution (e.g. Gilles *et al.*, 2011; Potlock *et al.*, 2023). A full understanding of the factors that characterise the variability of porpoise distributions could help distinguish the effects of wind energy development from that variability.

Finally, there may be some remaining uncertainty in the buzz classification method used in this study. Harbour porpoises produce NBHF clicks, with differences in click characteristics and ICI relating to different behavioural contexts (Verfuß *et al.*, 2009). High-repetition rate clicks (i.e. buzzes), have been identified in both foraging activity and social communication in porpoises (Clausen *et al.*, 2011; Sørensen *et al.*, 2018). In the present analysis, we are not able to distinguish between feeding buzzes and social communication.

However, Sørensen *et al.* (2018) estimated that about 74% of all high-repetition rate click trains may be related to feeding. We, therefore, assume the majority of such click trains are a measure of foraging effort, and in this study, we refer to them collectively as foraging buzzes. Futhermore, there are principally two methods used for identifying buzz vocalisations using PODs: the click-train based method (e.g. Pirotta *et al.*, 2014; Bergès *et al.*, 2019) and the click-based method (e.g. Carlstrom, 2005; Todd *et al.*, 2009). The click-train based method examines entire click-trains and identifies when search clicks (relatively stable ICIs around 50 ms) rapidly transition to ICIs below 10 ms (Verfuß *et al.*, 2009). In contrast, the click-based method simply applies a fixed ICI threshold (e.g. 10 ms) (Carlstrom, 2005; Todd *et al.*, 2009; Verfuß *et al.*, 2009). For efficiency in our analysis, we followed the click-based method; however, this method may be considered as more arbitrary than the click-train based method.

Results from this study provide valuable insights into porpoise occurrence and foraging and are intended to serve as a baseline to support the management of offshore wind energy developments. Construction and operation in WEAs in European waters have shown a wide range of effects on harbour porpoise such as displacement from their habitat and changes in behavioural responses (e.g. Tougaard *et al.*, 2006; Brandt *et al.*, 2011; Teilmann and Carstensen, 2012).

Identified as a focal species in regards to assessing the risks of WEA development in the United States (Southall *et al.*, 2021), these results highlight seasonal trends in occurrence patterns across numerous WEAs covering most of their range. Furthermore, when porpoises were present at a site, foraging was detected, demonstrating that porpoises forage wherever they are present. Thus, all sites within the SNE WEA and the GOM are important areas for this species, and mitigation measures during development should be considered. During installation, a suite of mitigation measures, such as bubble curtains, scaring devices, and ramp-ups are recommended to prevent temporary habitat loss and reduce the risk of hearing loss for harbour porpoises.

The GOM is in the early planning stages for the development of floating offshore WEA, with lease sales scheduled to begin in late 2024. Scheduling wind farm construction and associated activities in the GOM to take place during the winter months (when harbour porpoises' detections are lowest) would avoid their breeding season and reduce the likelihood of disturbance to porpoises (Gallagher *et al.*, 2021). In addition, water temperatures in the GOM are experiencing faster warming than any other ocean ecosystem (Pershing *et al.*, 2015). Warming waters are expected to have marked impacts on the distribution and life history of cetaceans (MacLeod, 2009, Chambault et al., 2022, Wild *et al.*, 2019), either directly through thermoregulation requirements or indirectly through impacts on productivity and prey availability (Martin *et al.*, 2023). Continued and expanded monitoring of porpoises and their behaviour in this region will be a critical component in future conservation efforts.

In the SNE WEA, there is a seasonal prohibition on pile driving activities from 1st January through 30th April when North Atlantic right whales are most likely to be present in the project area (NMFS, 2022b; Van Parijs et al., submitted). Harbour porpoise presence is high during this period; however, this timeline does not capture the entirety of this species presence. Therefore, additional monitoring and enhanced mitigation is needed from October to December and May through

July in order to minimise impacts. Furthermore, limiting activities during reduced light or darkness when porpoises are present and foraging would also minimise the likelihood of disturbance. As offshore wind energy development expands across the GOM and other US regions, it will be important to build on this approach in order to monitor potential changes in distribution.

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Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Author contributions

Amanda Holdman curated the data, conducted the formal analysis, investigation, and methodology, validated the data, generated the visualizations, and wrote and edited the manuscript. Annamaria I. DeAngelis supervised the project, including the investigation and methodology, assisted in generating visualizations, and reviewed and edited the manuscript. Nick Tregenza provided the resources and software for the project, and reviewed and edited the manuscript. Sofie Van Parijs led the project administration, conceptualization, acquired the funding, and reviewed and edited the manuscript.

Animal ethics and welfare

There are no animal ethics and welfare concerns.

Conflict of interest

The authors have no conflicts of interest to declare.

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Data availability statement

These data were collected with federal funding and are publically available upon request. We are working to integrate them into the publicly available Passive Acoustic Cetacean Map at https://apps-nefsc.fisheries.noaa.gov/pacm/#/

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