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Establishing baselines for predicting change in ambient sound metrics, marine mammal, and vessel occurrence within a US offshore wind energy area

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Evaluating potential impacts on marine animals or increased sound levels resulting from offshore wind energy construction requires the establishment of baseline data records from which to draw inference. This study provides 2 years of baseline data on cetacean species' presence, vessel activity, and ambient sound levels in the southern New England wind energy area. With eight species/families present in the area for at least 9 months of the year, this area represents an important habitat for cetaceans. Most species showed seasonality, with peak daily presence in winter (harbour porpoise, North Atlantic right, fin, and humpback whales), summer (sperm whales), spring (sei whales), or spring and fall/autumn (minke whales). Delphinids were continuously present and blue whales present only in January. The endangered North Atlantic right whales were present year round with high presence in October through April. Daily vessel presence showed an increase from summer through fall/autumn. On average, ambient sound levels were lowest in summer and increased late 2021 through 2022 with most temporal variability occurring across lower frequencies. The area showed a complex soundscape with several species sharing time–frequency space as well as overlap of vessel noise with the communication range of all baleen whale species.

Keywords: baseline data, cetaceans, North Atlantic right whale, offshore wind energy area, passive acoustic monitoring.

Introduction

Offshore wind energy development expansion has taken on a rapid pace with widespread development planned throughout the western Atlantic. Wind energy development is expected to grow significantly in the coming years, being enhanced by European, American, and global agreements (European Commission, 2018; Federal Sustainability Plan, 2021). The increasing development of large-scale wind energy projects raises environmental concerns about their cumulative effect, alongside other anthropogenic maritime activities (e.g. Masden *et al.*, 2010; Garel *et al.*, 2014).

Human impacts on marine ecosystems are increasing globally (Halpern *et al.*, 2015), and anthropogenic noise is a recognized pollutant, which has been shown to affect the behaviour, physiology, and fitness of animals (e.g. Slabbekoorn *et al.*, 2010). Noise from wind energy development activities may be either direct or indirect, likely to cause animals to change behaviour, impact effective communication, and increase stress responses (e.g. Madsen *et al.*, 2006; Francis and Barber, 2013; Pirotta *et al.*, 2014). Although these impacts are increasingly recognized, the cumulative impact of multiple concurrent long-term anthropogenic activities on populations is not well understood. This continues to be a major question in ecological research and a serious obstacle for sustainable environmental management (Sutherland and Freckleton, 2012).

Wind energy development is rapidly ramping up in US waters, poised to develop offshore wind area leases, comprising 1000s of turbines, throughout the Atlantic Outer Continental Shelf, as well as the Pacific and Gulf of Mexico, in order to meet renewable energy goals (Office of the Press Secretary, 2021, 2022). With a diverse suite of endangered large whale species and a multitude of other protected marine species frequenting these same waters, understanding the potential consequences of pre-construction, construction, operation, and decommissioning activities is essential to advancing responsible offshore wind development. In particular, rapid wind energy development of the Atlantic Outer Continental Shelf presents serious obstacles for sustainable environmental management since multiple endangered marine mammal species, such as the North Atlantic right whale, *Eubalaena glacialis* (Davis *et al.*, 2017), sei, *Balaenoptera borealis*, blue, *Balaenoptera musculus*, and fin, *Balaenoptera physalus*, whales (Davis *et al.*, 2020), and sperm whale, *Physeter macrocephalus* (Stanistreet *et al.*, 2018) inhabit these waters. Additionally, all other cetacean species in US waters are also protected under the Endangered Species Act and Marine Mammal Protection Act.

Passive acoustic monitoring (PAM) allows for understanding trends in species distribution, habitat use, cumulative impacts and risk mitigation, and evaluating potential behavioural and distributional changes resulting from wind energy development (e.g. Estabrook *et al.*, 2022; Murray *et al.*, 2022). In this study, we demonstrate standardized methodologies for understanding baseline information in one of the earliest wind energy areas to be developed, off the coast of southern New England, US. The construction phase in two lease areas started in the spring of 2023 and will be closely followed by the development of other lease blocks. Van Parijs *et al.* (2021) recently developed a set of minimum guidelines for

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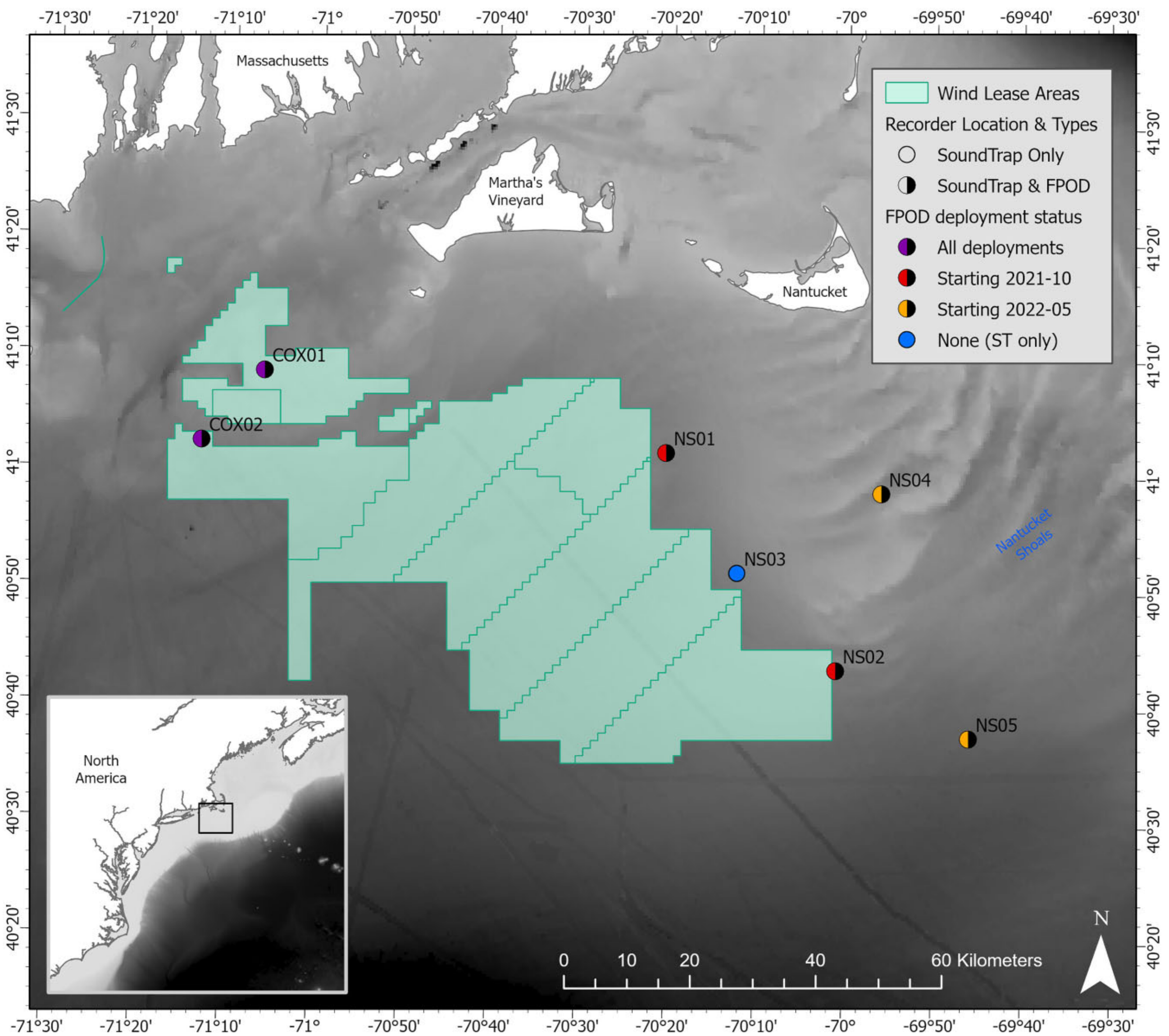

Figure 1. A map of the southern New England planned offshore wind energy lease areas off the East Coast of the United States (insert). Passive acoustic recorders (SoundTrap and F-POD recorders) were deployed for varying time periods (see Table 1) between January 2020 and November 2022 at seven sites surrounding the wind energy areas. Bathymetry layer provided by GEBCO Compilation Group (2022) GEBCO_2022 Grid (doi:10.5285/e0f0bb80-ab44-2739-e053-6c86abc0289c).

PAM monitoring and mitigation relative to wind energy area development. Here, we demonstrate how PAM can be used to provide a baseline understanding of all cetacean species frequenting the area in addition to establishing current levels of vessel activities and ambient sound trends. These standardized baseline data will enable precautionary management decisions to be made by guiding the timing of seasonal closures, risk mitigation measures, and allow future evaluation of potential impacts.

Methods

This study took place around the southern New England, US offshore wind energy area from January 2020 to November 2022 (Figure 1). This area comprises nine separate wind energy lease blocks that span across Massachusetts to Rhode Island state waters and into US federal waters. Seven bottom mounted acoustic recorders (SoundTrap500, 600; self-noise is less than sea-state 0 at 100 Hz–2 kHz and <36 dB re 1μPa above 2 kHz; system end-to-end calibration: −175.1 to −177.6 dB re 1 V/μPa; Ocean Instruments, Inc.) were deployed in locations both surrounding and within parts of this wind energy area. Four locations recorded continuously for over 2 years, while the others varied from 4 to 9 months. The recorders were configured to sample ambient sound continuously. SoundTraps have a large dynamic range (16-bit A/D converter) and flat frequency response (±3 dB) between 20 Hz and 60 kHz, providing an effective recording range for this study of 20 Hz to 32 kHz (Table 1). In addition, high-frequency click detector F-POD recorders (Chelonia Ltd) were collocated with some of the SoundTraps. F-POD deployments varied between sites ranging from almost 2 years to 5 months over the duration of this study (see Table 1). F-PODs store cetacean clicks in the range of 17 to 210 kHz. Using VEMCO VR2AR acoustic release receivers and weights, passive acoustic recorders were attached 2–3 m above a fixed bot-

Table 1. This study had two different recorder types SoundTrap (500 or 600 model) and F-PODrecorders collecting acoustic data across seven sites.

Site	Recorder type(s)	Latitude	Longitude	Depth (m)	Sample rate (kHz)	Start date (dd/mm/yy)	End date (dd/mm/yy)	Days analysed (*n*)
Cox01	ST500 & 600	41.14128	−71.10312	32	48–64	15/11/20	09/10/22	689
	F-POD	41.14128	−71.10312		1000	15/11/20	31/8/22	634
Cox02	ST500 & 600	41.03937	−71.21892	41	48–64	15/11/20	18/10/22	683
	F-POD	41.03937	−71.21892		1000	15/11/20	22/10/22	689
NS01	ST500 & 600	41.03343	−70.34125	38	48–64	23/01/20	29/05/22	842
	F-POD	41.03343	−70.34125		1000	13/10/21	29/5/22	228
NS02	ST500 & 600	40.73645	−70.01428	32	48–64	23/01/20	09/11/22	1010
	F-POD	40.73645	−70.01428		1000	14/10/21	27/10/22	378
NS03	ST600	40.86260	−70.20480	38	64	07/02/22	29/05/22	111
NS04	ST600	40.97809	−69.93346	32	64	07/02/22	09/11/22	275
	F-POD	40.97809	−69.93346		1000	30/05/22	09/11/22	163
NS05	ST600	40.62812	−69.76597	58	64	07/02/22	09/11/22	275
	F-POD	40.62812	−69.76597		1000	30/05/22	09/11/22	163

The location (site), depth, frequency sampling rate, site coordinates (latitude/longitude), start and end dates of recordings, and the number of days available for acoustic analysis are provided.

tom mounted mooring with subsurface floats extending ~6 m vertically into the water column.

Baleen whale acoustic analyses

Two automated detection software packages, the Low-Frequency Detection and Classification System (LFDCS; Baumgartner and Mussoline, 2011) and a custom Python script were used to extract the calls of six species of baleen whales. The LFDCS acoustic software focuses on detection of the following call types; North Atlantic right whale upcall, humpback whale (*Megaptera novaeangliae*) song and non-song, fin whale 20 Hz pulse, sei whale downsweeps, and blue whale song. The custom Python script was used to detect minke *(Balaenoptera acutorostrata)* whale pulse trains. SoundTrap acoustic data were processed using the LFDCS. After tracing contour lines, or "pitch tracks" through tonal sounds, the programme uses multivariate discriminant function analysis to classify the pitch tracks into species-specific call types based on a call library. Each detection is assigned a Mahalanobis distance (MD), which measures the deviation of a sound's pitch track from the assigned call type. A lower MD indicates a closer match and a threshold of 3.0 was chosen for all call types detected and classified in the North Atlantic right whale upcall, humpback song and non-song, sei downsweep, and fin 20 Hz pulse call libraries (described in Davis *et al.*, 2020; Supplementary Table S1). For blue whale song, false detection rates were lower than any of the other species, thus an MD of 5.0 was chosen to decrease the probability of missing true detections. The LFDCS detections were manually reviewed by a number of trained acoustic analysts to determine the minimum daily acoustic presence of each of the five baleen whale species (Wilder *et al.*, 2023).

Minke whale pulse trains were automatically detected using a ResNet18 convolutional neural network (CNN) classifier similar to the one described in Kirsebom *et al.* (2020). It was implemented in Python and used the Ketos library (https://docs.meridian.cs.dal.ca/ketos). The CNN was trained using annotations from 24 different deployments located both off the east coast of the United States and off Scotland, United Kingdom, resulting in a dataset of 2222 minke whale pulse trains and 16004 non-minke whale sounds (which included humpback whale songs, haddock pulsed calls, pile driving noise, vessel noise, and ambient noise). The CNN was configured to perform a binary classification task (i.e. minke whale vs. non-minke whale) on 2 kHz sampled data based on 5 s long spectrogram images between 0 and 800 Hz computed using a STFT (window size = 256 samples; 50% overlap; hann window). Once the CNN model was trained, it was run on continuous acoustic recordings and a probability score between 0 and 1 was assigned to each classification. To assess the performance of the detector, we ran it on 1 year of continuous data from this study (NS01) that were not used for training the classifier and were manually annotated by experienced analysts. Keeping detections with a classification score higher than 0.8 captured most of the daily presence of minke whales (95%) while minimizing false alarms (26% days with false alarms). Consequently, the detector was run on all the SoundTrap data with a minimum classification score threshold of 0.8. Automatic detections were then manually reviewed to confirm the minimum daily acoustic presence of minke whales.

Sperm whale acoustic analyses

Long-Term Spectral Average (LTSA) files were created from the SoundTrap recordings as a first step for both the sperm whale and vessel detection analyses (see below). These files were generated using the Triton package (https://www.cetus.ucsd.edu/technologies_triton.html) within the MATLAB software (MathWorks Inc., Natick, MA) by concatenating the acoustic data for each deployment and calculating sound levels as a function of time (5 s bins) within specified frequency ranges (48 Hz increments). These files were then processed through batch detectors for visual inspection and validation of sperm whale and vessel detections.

Sperm whale echolocation clicks were identified using an automated multi-step detection algorithm (Solsona-Berga *et al.*, 2020) designed to run on LTSA files in MATLAB R2016b (Solsona-Berga *et al.*, 2022). The detector applied a bandpass filter between 5 and 23 kHz to reduce background noise. Detections were filtered to remove other odontocete (e.g. delphinid) clicks based on sperm whales' low-frequency spectral click shape and at a received level threshold of 130 dB_{pp}. The remaining detections were manually reviewed and false positives were removed using *DetEdit*, *a multi* stage detection programme (Solsona-Berga *et al.*, 2020). Sperm whales were considered to be present on a given day if at least 1 min contained five or more confirmed sperm whale clicks.

Vessel presence analyses

Vessel presence was identified using the Ship Detector Remora in the Triton software package described by Solsona-Berga *et al.* (2020, Supplementary Material; https://github.com/MarineBioAcousticsRC/Triton/tree/master/Remoras/Ship-Detector) and run on the LTSA files generated as described in the section above. Similar to Merkens *et al.* (2021) the detector computed the average power spectral densities (APSD) per 5-s time bin across three LTSA frequency bands, low (50 Hz–3 kHz), medium (3–10 kHz), and high (10–17 kHz). The adaptive thresholds were determined over sequential 2 hourly windows to identify periods of transient signals above ambient noise. When energy in the lower two or all three frequency bands exceeded specified thresholds for longer than 150 s, the time period over which the thresholds were exceeded was identified as a vessel passage. The frequency range of the low, medium, and high bands and the duration of the presence threshold were selected to maximize the number of true positive vessel detections while minimizing the rate of false positives. Using the values of true positives and false positives, precision was calculated as in Baumgartner *et al.* (2019) in order to assess detector performance. The detections from this tool are likely an underestimate of vessel presence, particularly during daytime hours, because the dynamic nature of the tool means that 2 h windows with a large amount of continuous vessel energy will have a higher threshold and therefore only extremely high-energy vessel signals will be detected. Daily percentage of vessel presence (presented as ratios) was calculated as the number of hours with confirmed vessel detections per total recording hours for a given calendar day.

Delphinid acoustic analyses

Within our study area, the delphinids that are likely to occur are bottlenose dolphin (*Tursiops truncatus*), common dolphin (*Delphinus delphis*), Atlantic white-sided dolphin (*Lagenorhynchus acutus*), and pilot whale species (*Globicephala* sp.) (Hayes *et al.*, 2022). These species produce whistles, clicks, and burst pulses used in both communication and forging (e.g. Steiner, 1981). At present, species-specific classification is limited due to the small sample size of acoustically verified recordings. Thus, we followed similar methods as described by DeAngelis *et al.* (2022) and grouped all received whistles into a "delphind species" category. The presence of clicks and burst pulses were not used for this analysis as whistles alone sufficiently capture presence at the daily scale. As described in DeAngelis *et al.* (2022), a simple Whistle and Moan Detector was run using the acoustic software PAMGuard (v. 2.01.03, Gillespie *et al.*, 2008). Hours with the most whistle detections in a day were examined first, and if that hour contained only false positives, the subsequent hour with the highest number of detections was examined, until either a delphinid whistle was found, or all hours in a day containing detections were reviewed.

Harbour porpoise acoustic analyses

Upon recovery, acoustic data from F-PODs were downloaded and processed using the FPOD.exe software (v1.0, https://www.chelonia.co.uk/index.html) and the built-in KERNO algorithm was used to detect click trains. The KERNO-F algorithm assigns click trains into four different potential sources of origin: "NBHF (narrow-band high-frequency)", "Other Cetacean", "Sonar", and "unclassed", and filters the quality of the click trains into different categories; "High", "Moderate", and "Low". Following the Chelonia criteria (see https://chelonia.co.uk/fpod_downloads.html), all NBHF click trains were attributed to harbour porpoise, and only click train qualities "Moderate" or "High" were used in subsequent analyses, as is consistent with other studies using PODs (e.g. Todd *et al.*, 2022). The frequency, species class, train quality class, and click rate of all click trains were viewed graphically on a 20 ms time-scale and several waveforms of individual clicks were viewed to assess individual click frequency. To minimize the false positive rate, 100 randomly selected sample points from the NBHF data from each deployment period were visually verified following guidelines from the manufacturer (https://www.chelonia.co.uk/index.html); suspect detections were removed from analysis (Holdman *et al.*, 2023, submitted). Minutes containing five or more consecutive NBHF clicks were extracted from FPOD.exe and summarized into a binomial daily presence to describe seasonal occurrence patterns.

Visualizing species acoustic niches

Acoustic signals were grouped into ten categories, which include six mysticete and three odontocete categories, as well as one anthropogenic signal. For visualization purposes, the chosen frequency bands were not necessarily intended to represent the entire frequency range for each of the species groups but instead to represent the band that captured the majority of their acoustic energy while still allowing for visual discrimination between species groups in the graphics (as in Weiss *et al.*, 2021). Where possible, frequency ranges were the same as in Weiss *et al.* (2021) with the exception of minke whales (50–300 Hz; Risch *et al.*, 2013) and harbour porpoises (120–160 kHz; Southall *et al.*, 2019). The delphinid frequency range was adapted to encompass a whistle frequency range (2–18 kHz; Herzing, 1996), as opposed to the click range reported in Weiss *et al.* (2021). For blue whales, the upper range of the representative frequency (15–90 Hz) was updated from 20 Hz to better reflect their calling range (Wingfield *et al.*, 2022). For each signal type, the overall frequency range and daily occurrence of that signal were graphed with spectrographic box displays (SBDs) (Van Opzeeland and Boebel, 2018). Data visualizations were created using the software package R 3.5.1 (R Core Development Team) and the library *tidyverse*.

Ambient sound level analyses

Ambient sound pressure levels (SPLs) of data collected by SoundTraps were calculated within MATLAB using the Soundscape Metric Remora of the Triton Software Package (https://github.com/MarineBioAcousticsRC/Triton/tree/master/Remoras/Soundscape-Metrics). For each deployment, power spectral densities (PSD) were generated in 1 Hz/1 s bins (window size and FFT length = sample rate; 0% overlap; hann window) from 10 Hz to 24 kHz and saved as mean-square sound pressure spectral densities (μPa^2/Hz). Mean broadband (10 Hz–24 kHz) and decidecade (one-third octave) SPLs per minute were calculated by integrating the mean-square sound pressure spectral densities over their respective frequency bands, computing the arithmetic mean per minute, and converting to decibels (dB re 1 μPa) (see Merchant *et al.*, 2015). Resulting decidecade SPLs corresponded

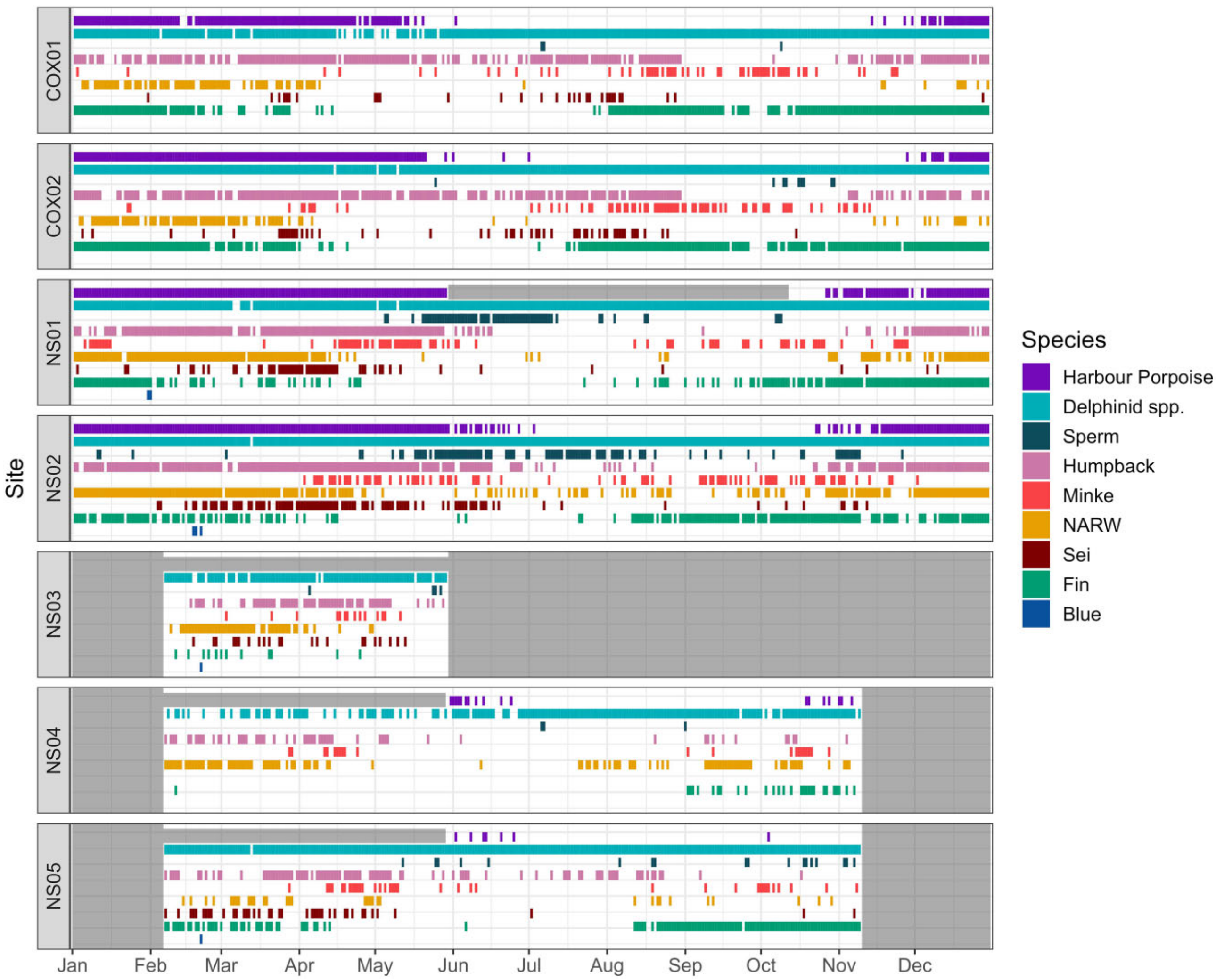

Figure 2. Acoustic daily presence of eight cetacean species (harbour porpoise, sperm whale, humpback whale, minke whale, North Atlantic right whale (NARW), sei whale, fin whale, blue whale) and one family (Delphinid sp.), compiled across all recordings at all seven southern New England offshore wind energy areas from January 2020 to November 2022. Less recording effort was available for NS03–05 (see Table 1). The grey blocks indicate where no data were available during those months at that site (for harbour porpoise, additional grey blocks indicate where no F-POD data were available).

to standard frequency bands ranging from nominal centre frequencies of 25 Hz to 20 kHz (IEC, 2014). Mean broadband and decidecade SPL per minute were used as base measures for all subsequent analyses and statistics.

Broadband and decidecade SPLs were concatenated across all deployments at each of the seven recording sites to examine temporal, spatial, and spectral trends. Days in which data were missing due to instrument malfunctions or gaps between deployments were omitted from further analysis. Daily medians of all 1 min, mean measurements of broadband and decidecade SPL were calculated to visualize measures of amplitude as a function of time and frequency (i.e. decidecades) across complete datasets. Annual and cumulative means, medians, distribution percentiles (10th and 90th), minimums, and maximums were generated to provide baseline summaries of amplitude and range (i.e. variability) at each site; means were calculated as root-mean-squares (rms) of sound pressure levels in the linear domain. Monthly and hourly medians and percentiles (10th and 90th) of broadband SPL were calculated to examine temporal trends and evaluate diel patterns, respectively, at each monitoring location. Seasonal medians of decidecades were generated to assess the frequency characteristics of ambient sound at each site and possible differences among years, seasons, and sites. Seasons are defined as spring (March through May), summer (June through August), fall/autumn (September through November), and winter (December through February).

Results

Cetacean activity

Acoustic daily presence of eight cetacean species and one family (Delphinids) was compiled from January 2020 to November 2022 (Figure 2). Less recording effort was available for NS03, 04, and 05 (see Table 1). Figure 3 focuses solely on the recorders for which there were 2 or more years of data (NS01, NS02, COX01, COX02) with weekly summaries of each species'/family' daily presence.

Monthly presence across all sites

Acoustic presence was similar across all sites for all species/family with greatest daily persistence at both NS01

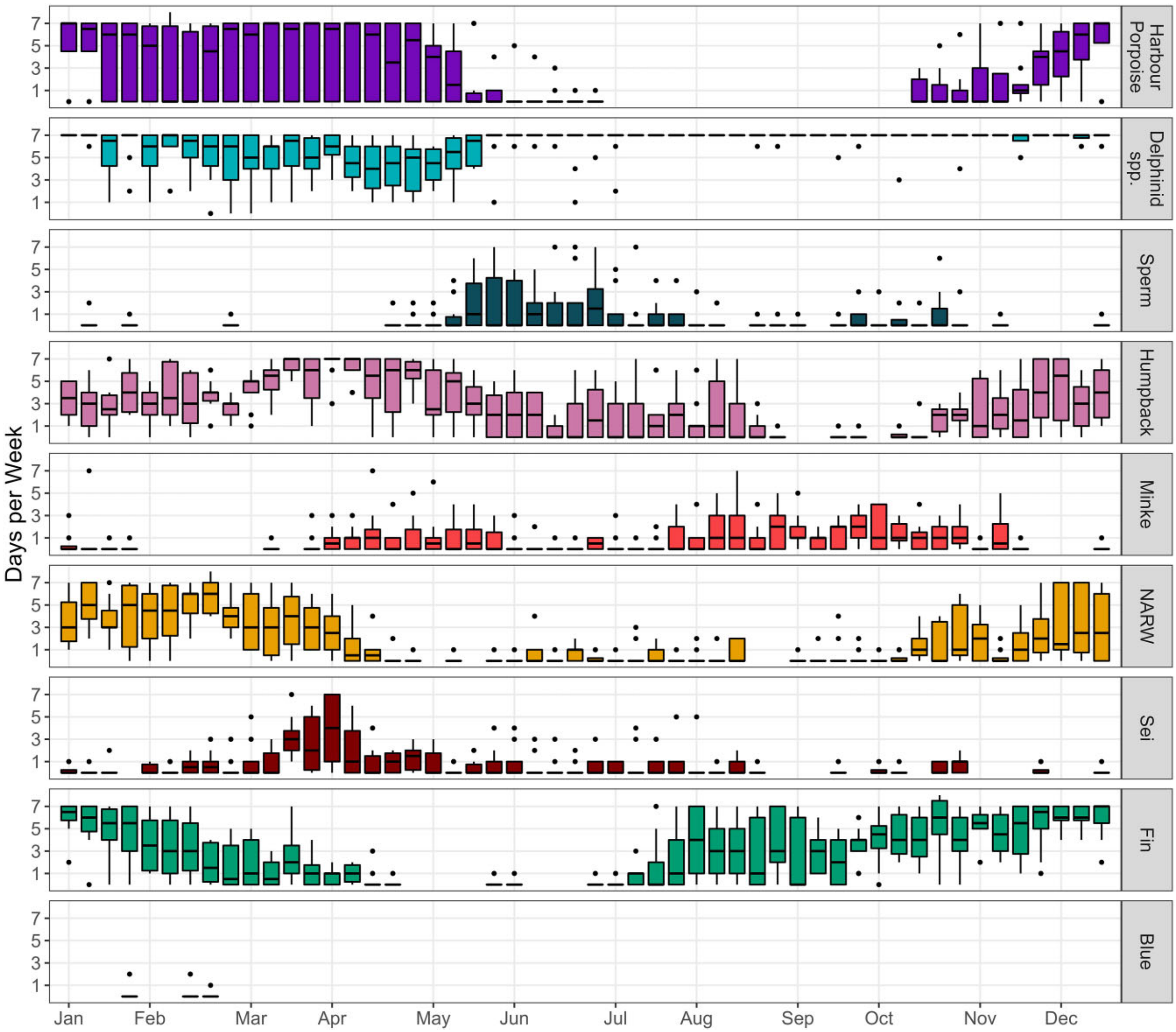

Figure 3. Weekly acoustic presence summary of eight cetacean species (harbour porpoise, sperm whale, humpback whale, minke whale, North Atlantic right whale (NARW), sei whale, fin whale, blue whale) and one family (Delphinid sp.). The boxplots represent the median number of days of acoustic presence per calendar week across all data at four recording sites, in the southern New England offshore wind energy area. Only recorders with 2 or more years of data (NS01, NS02, COX01, and COX02) were used. Horizontal lines within the boxes indicate the median, box boundaries indicate the 25th (lower quartile) and 75th (upper quartile) percentiles, vertical lines indicate the largest (upper whisker) and smallest (lower whisker) values no further than 1.5 times the interquartile range, and black dots represent outliers.

and NS02 sites (Figure 2). Harbour porpoises were present across COX01, COX02, NS01, and NS02s from December through May with more sporadic presence in June, October, and November at NS03–05. Delphinids were continuously present year round across all sites. Sperm whales showed occasional presence from May through November across all sites, with most daily presence at NS01 and 02. Humpback whales were acoustically present year round at COX01, COX02, NS01, and NS02, with greatest presence from November through to June. Although also present on NS03–05, they showed more sporadic daily presence. Minke whales were present at all sites from March through June and August through November/early December. Additional presence was observed in January for COX01, 02, and NS01. North Atlantic right whales were present September through May with sporadic presence in June through August across all sites. NS02 was the site with the most persistent year round presence of North Atlantic right whales. More detailed information on North Atlantic right whale up calling behaviour can be found in Davis *et al*. (submitted). Sei whale presence was greatest February through June and July through August at all sites besides NS04, where they were not detected. Fin whales were present at all sites from August through April, with sporadic presence from May through July. COX02 was the only site to show high levels of daily presence of fin whales in July. Blue whales were rarely present but were heard on a few days in January and February on NS01–03, and NS05. No blue whales were detected on COX01, COX02, or NS04.

Weekly seasonal patterns across four sites

Examining the weekly presence summarized across years allows for an improved understanding of how frequently each of the species/family were acoustically active and whether they exhibit seasonal patterns in their activity (Figure 3). **Winter Presence:** harbour porpoise, North Atlantic right whale, fin, and humpback whales all showed consistent presence throughout the winter months and a decrease in summer months. **Summer Presence:** Sperm whale acoustic presence was also seasonal in nature with a peak in late spring and summer (May to July) with a maximum of 4 d a week of presence. There was sporadic presence of between 1 and 2 d a week across all other months except for March when no acoustic activity was heard. **Spring Presence:** Sei whales showed a peak in late winter and early spring (February to May) with sporadic presence throughout all other months. **Spring and Fall/Autumn Presence:** Minke whales saw increased activity in the spring, with a maximum of 2 d a week of presence (April/May) and a prolonged increase in summer through fall (July to November) with a maximum of 4 d a week of call presences. **Continuous Seasonal Presence:** Delphinids showed no seasonal pattern and were acoustically active 7 d a week, with only a slight decrease in activity in March and April. **Occasional Presence:** Blue whales were only present on a few occasions in the winter (January/February).

Vessel activity

Across the sites with 2 or more years of recording effort (NS01, NS02, COX01, and COX02), the total number of detections ranged from 10578 to 12927. The precision of the vessel detector was between 0.831 and 0.869% for these sites.At NS03, NS04, and NS05, the total number of all detections ranged from 1635 to 4120. The precision of the detector ranged from 0.56% at NS04 to 0.84% at NS05. The percentage of hours with true vessel detections was similar across most sites with averages of 10 to 50% presence across a 24 h period and no clear visible diel pattern (Figure 4A). NS03 and 04 showed the lowest hourly vessel detections. Vessel detections varied throughout the year, with higher values for detected events occurring during the summer (June–August) at all sites with effort during that season (Figure 4B). At NS01, COX01, and COX02, this general peak in activity extended into the autumn months (September–November).

Species acoustic niches

Spectrographic box plots of the four sites (COX01, COX02, NS01, and NS02) with over 2 years of data were generated by combining all categories of cetaceans and vessel presence in order to explore the overlap in frequency ranges and masking potential (Figure 5). Most biological categories showed frequency and temporal overlap with at least one other category across all sites. The baleen whales—North Atlantic right, humpback, minke, sei, fin, and blue whales—generally had a high degree of frequency overlap, with blue, sei, North Atlantic right, and humpback whales all occupying frequencies between 50 and 100 Hz. Vessel noise is broadband and present on each day of recording, and the dominant frequencies of vessel noise overlap with all baleen whale species and partially with sperm whales.

Ambient sound levels

Broadband SPLs

Median broadband SPLs of all available data at each site ranged from 105 to 112 dB (re 1 μPa) with some variability among sites and years (Supplementary Table S1). Sites NS03, NS04, and NS05 yielded the highest overall median broadband SPLs but resulted exclusively from limited recordings in 2022. Median broadband SPLs increased from 2020 to 2022 at COX02, NS01, and NS02 by up to 4 dB (range = 0.9–4.2 dB), while similar increases were not observed at COX01. Within sites and years with at least 6 months of data, the variability, as estimated by the amplitude of differences between the 90th and 10th percentile levels (Δ), was highest at NS04 in 2022 ($\Delta = 29.3$ dB) and lowest at COX01 in 2021 ($\Delta = 11.5$ dB), while differences at the remaining sites varied between 11.6 and 17.2 dB within years. Daily median broadband SPLs were variable within and among sites, ranging from 96 to 129 dB (re 1 μPa; Supplementary Figure S1). Monthly median levels trended higher in winter and early spring compared to other months at COX01, COX02, NS01, and NS02; although the persistence of above median levels increased from mid-2021 into 2022, eroding the seasonal effect observed in previous years (Supplementary Figure S2). No diel patterns were observed in SPLs at any of the sites.

Decidecade SPLs

Median decidecade SPLs varied among sites, years, and decidecade bands but yielded important information to assess baseline patterns of the soundscape and putative future changes within the southern New England offshore wind energy area (Supplementary Table S2). Examination of daily median decidecade SPL further elucidated patterns observed in broadband results, highlighting the commonness of higher amplitudes at lower frequencies compared to higher frequencies within the soundscape and their role in driving amplitudes of broadband SPL (Figure 6). Sources of sound above ambient background noise were largely below 1 kHz with intermittent days of elevated decidecade SPLs approaching the 10 kHz centre frequency band.

The seasonal spectral characteristics of soundscapes across all sites indicated that ambient decidecade levels were highest across lower frequencies with a tendency to decrease in amplitude beyond frequencies of 50–80 Hz (Figure 7). Exceptions to this trend were observed at COX01 and COX02, which had more static amplitudes across higher frequency bands outside of summer in 2021 and 2022. Beyond a frequency of ~100 Hz, decidecade levels were lowest in summer compared to other seasons at COX01 and COX02, and beyond 1 kHz, seasonal levels were similar across years. Within lower frequencies, the effect of season was more variable as a function of year and season at these two sites, where COX01 and COX02 exhibited higher levels in winter, spring, and fall/autumn starting in 2021. Trends in decidecade SPLs as a function of frequency were similar at NS01 and NS02, but differences in amplitude were also observed as a function of year and season. At NS01, levels increased across lower frequencies starting in summer 2021 and remained elevated until the end of data collection in spring 2022. This noticeable increase at NS01 starting in 2021, was less evident at NS02. At NS02, levels below ~1 kHz were higher in fall/autumn 2021, winter 2022, summer 2022, and fall/autumn 2022 compared to seasons in other years; spring was less predictive of SPLs

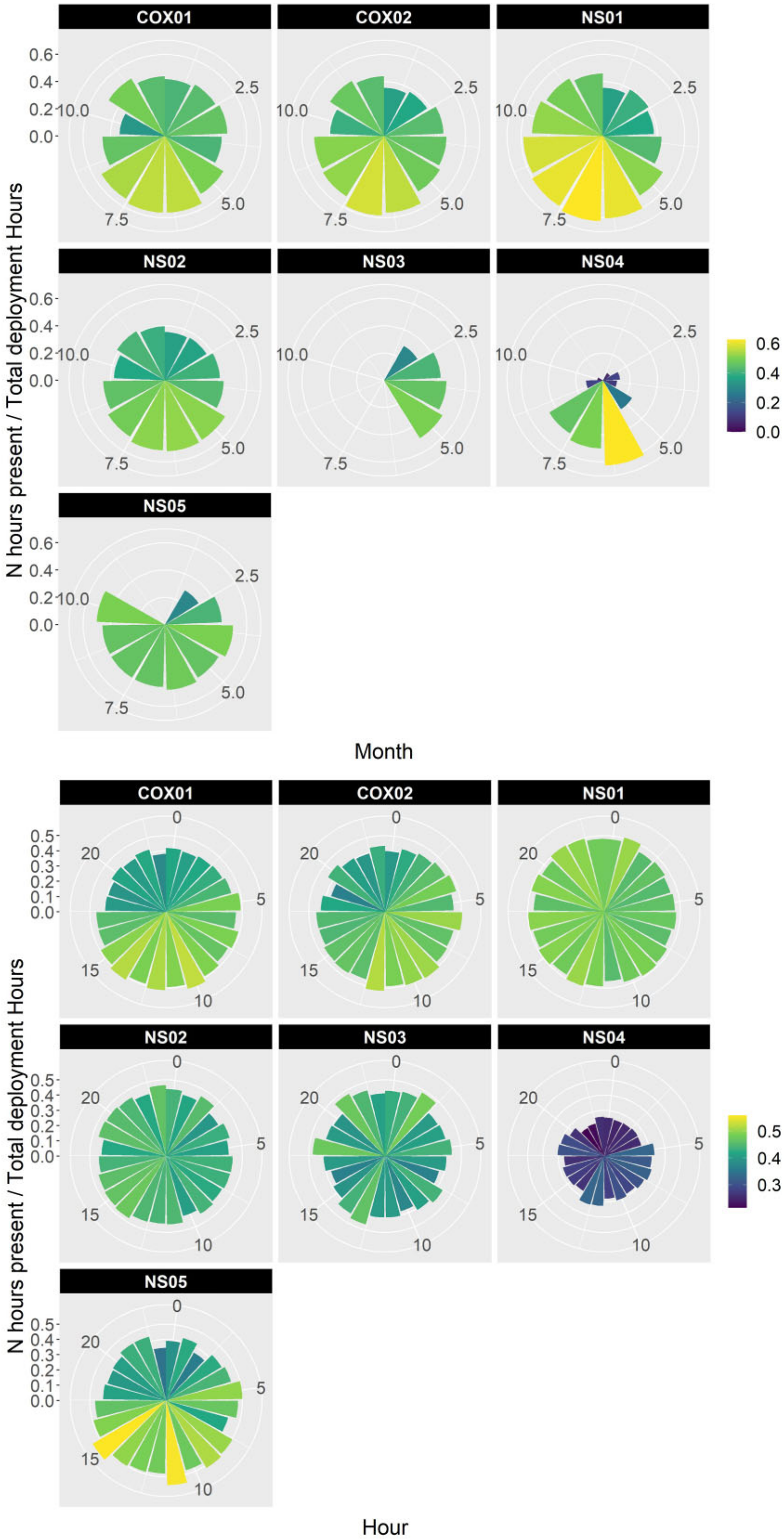

Figure 4. The number of vessel detections/the number of deployment hours represented as ratios (0–1) by (**A**) hour (24 h) and (**B**) month (12 months) compiled across all recordings at all seven southern New England offshore wind energy areas from January 2020 to November 2022. The colour scale is darker at a lower ration (less vessels) compared to lighter at a higher ratio (more vessels).

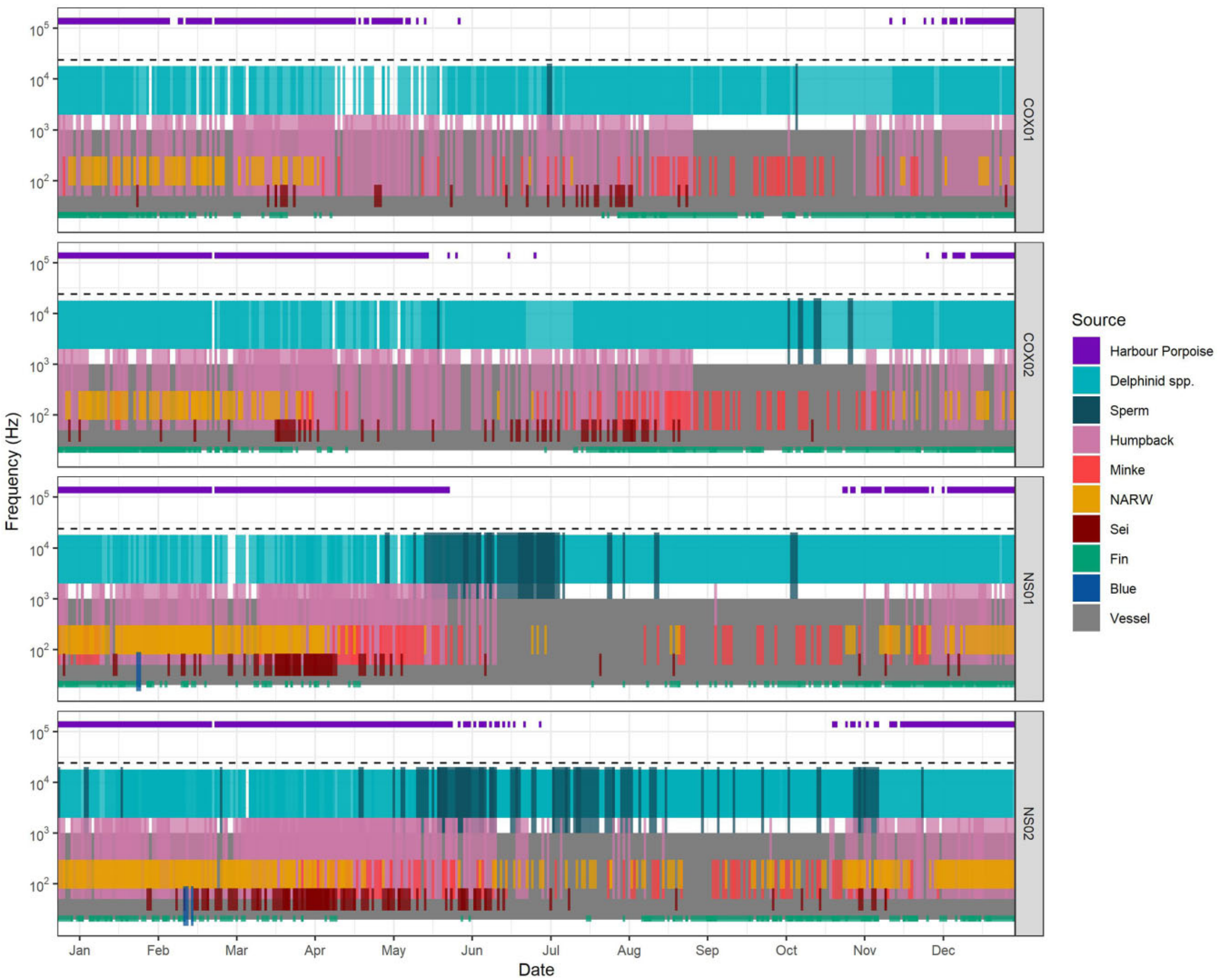

Figure 5. Acoustic niche representation through spectrographic box displays of daily presence and dominant frequencies of all cetacean sources (harbour porpoise, sperm whale, humpback whale, minke whale, North Atlantic right whale (NARW), sei whale, fin whale, blue whale) and one family (Delphinid sp.) and vessels summarized from 2 years of passive acoustic recording across the four recording sites, in the southern New England offshore wind energy area. The black-dotted line indicates the 24 kHz Nyquist frequency of some of the acoustic recorders used in this study.

across all years but also saw a slight increase in 2022 at centre frequencies of 63–80 Hz. The sparsity of data at NS03, NS04, and NS05 prevented interannual comparisons among seasons, but levels were higher across all frequencies in winter vs. spring 2022 at NS03, disproportionately higher below 100 Hz during winter and spring 2022 at NS04, and relatively uniform at NS05.

Discussion

This study provides 2 years of baseline data on cetacean species' presence, vessel activity, and ambient sound levels in the rapidly developing southern New England offshore wind energy area. Important areas for cetaceans are spatially defined areas where aggregations of individuals of a species are known to display biologically important behaviours, such as breeding, foraging, resting, or migration (e.g. Notarbartolo di Sciara and Hoyt, 2020; Harrison *et al*., 2023). With eight species and one family of cetaceans, of which eight are present a minimum of 9 months of the year, southern New England can be defined as an important biological area for cetaceans.

Baleen whale distribution went through a significant shift in species distribution around 2010 reflected in an increased use of the southern New England region (Davis *et al*., 2017, 2020). The importance of Nantucket Shoals as a feeding ground for the critically endangered North Atlantic right whales within the southern New England wind energy is well understood (Leiter *et al*., 2017; Quintana-Rizzo *et al*., 2021; Estabrook *et al*., 2022). Similarly, year round presence of this species has been demonstrated since as early as 2011 (Quintana-Rizzo *et al*., 2021; Estabrook *et al*., 2022), showing that North Atlantic right whales have consistently used this region for well over a decade. Currently, the National Marine Fisheries Services and Bureau of Ocean Energy Managements policy is to exclude pile driving during the months of January through April in the southern New England wind energy area. Evaluation of the need for further management protections are needed for North Atlantic right whales especially in October through December, along with further assessment of risk to this species (Southall *et al*., 2023). Humpback, fin, sei, and blue whales form part of routine aerial surveys and passive acoustic monitoring programmes within the northwestern Atlantic Ocean.

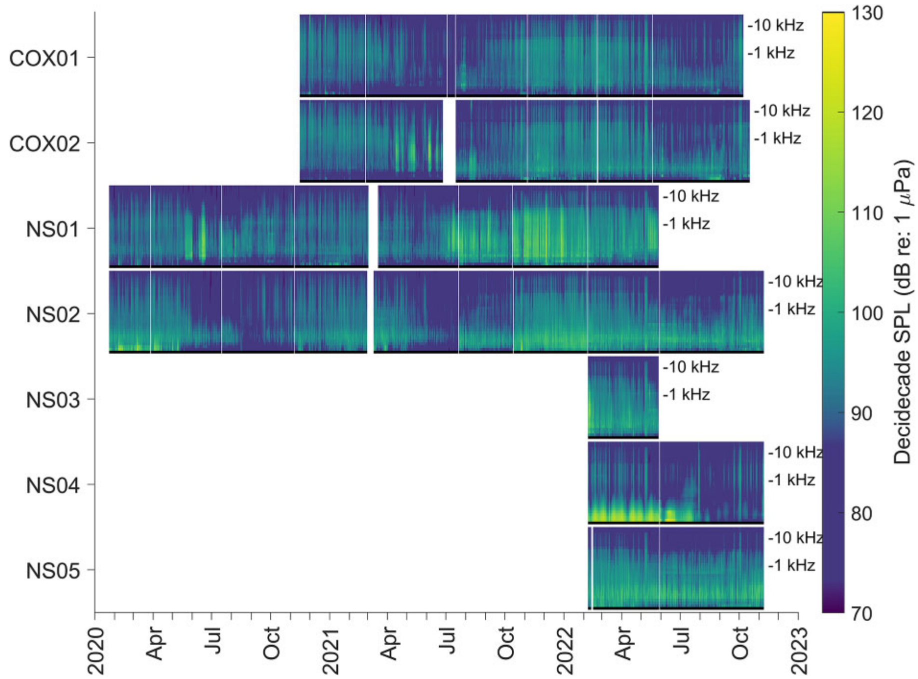

Figure 6. LTSA of daily median, decidecade sound pressure levels (dB re 1 μPa) at sites COX01, COX02, NS01, NS02, NS03, NS04, and NS05 in the southern New England offshore wind energy area. Within each site, daily medians of decidecades with nominal centre frequencies of 25 to 20000 Hz are stacked vertically; bottom = 25 Hz and top = 20000 Hz nominal frequency. The vertical dimensions of decidecade bands are equivalent to assist the interpretation of lower frequencies and thus, are not scaled by frequency bandwidth. Time periods without data are depicted in white.

As of 2010, these species show similar trends in the southern New England to those observed in this study (Davis *et al.*, 2017; 2020, https://apps-nefsc.fisheries.noaa.gov/pacm/#/, https://whalemap.org/).

Much less is known about the distribution, occupancy, and behaviour of the other species, the sperm whale, the minke whale, the harbour porpoise, and delphinids, in the southern New England wind energy area area. This study shows that they are regularly present within or near to the southern New England wind energy area. Sperm whales were predominantly present in southern New England in the spring and summer. This is consistent with previous surveys in the area (Waring *et al.*, 2014; Stanistreet *et al.*, 2018) including regular visual sightings of sperm whales inshore of the shelf break (Scott and Sadove, 1997). This region of the western North Atlantic is an important seasonal habitat for sperm whales (Westell *et al.*, 2022), especially in the southern New England area where sperm whales travel into shelf waters to forage on migrating squid (CETAP, 1982). Harbour porpoises were present for 9 months, absent only in July through September, demonstrating that the southern New England wind energy area is an important area for this species. The effects of offshore wind energy pile driving have been extensively studied for harbour porpoise throughout Europe where a wide range of responses have been documented, from behavioural changes, site avoidance to decreased foraging (e.g. Tougaard *et al.*, 2009; Brandt *et al.*, 2012; Kastelein *et al.*, 2013; Nels *et al.*, 2016; Schaffeld *et al.*, 2020; Benhemma-Le Gall *et al.*, 2021). Due to their small size and high energetic needs, this species is especially vulnerable to disturbance (e.g. Wisniewska *et al.*, 2016; Booth, 2020). Delphinids were present continuously throughout the southern New England wind energy area. Species discrimination remains a challenge for this family due to the wide range of sounds produced that are similar in structure, frequency range, and contour. However, visual surveys indicate that bottlenose dolphin, common dolphin, Atlantic white-sided dolphin, and pilot whale species commonly use this area (Hayes *et al.*, 2022). A range of impacts of pile driving on delphinids has also been demonstrated from changes in behaviour such as avoidance to changes in vocalizations (e.g. Graham *et al.*, 2017; Branstetter *et al.*, 2018). Further expansion following the PAM Framework (Van Parijs *et al.*, 2021) including F-POD recorders aims to address changes in relative abundance, behaviour, and distribution, as well as foraging effort for harbour porpoise and delphinids (e.g. Carlén *et al.*, 2018; Owen *et al.*, 2021).

Offshore wind energy development encompasses a wide range of underwater sound in addition to the noise produced through pile driving (e.g. Ruppel *et al.*, 2022). These sounds are produced at varying times during the exploration, preparation, and construction of a wind energy area and need to be identified and characterized as a contributing factor to an area's soundscape. In addition to these sound sources, underwater noise produced by vessels increases the risk of masking the acoustic communication space of cetaceans (e.g. Cholewiak *et al.*, 2018). In the southern New England wind energy area, vessel presence varied between 10 and 50% daily with an increase in traffic in the summer and fall period. In many areas of high vessel traffic along high population density coastlines, vessel activity tends to be continuous throughout the day and night (e.g. Haver *et al.*, 2020). Acoustic niche plots showed the significant frequency overlap of vessel noise with all baleen whale species in the area. With the New York shipping lane passing due south of the southern New England, fishing vessels and preliminary wind energy operations underway, this area like many others along the US seaboard are already exposed to near continuous vessel traffic (e.g. Hatch *et al.*, 2008). Increased numbers of vessels as a result of wind

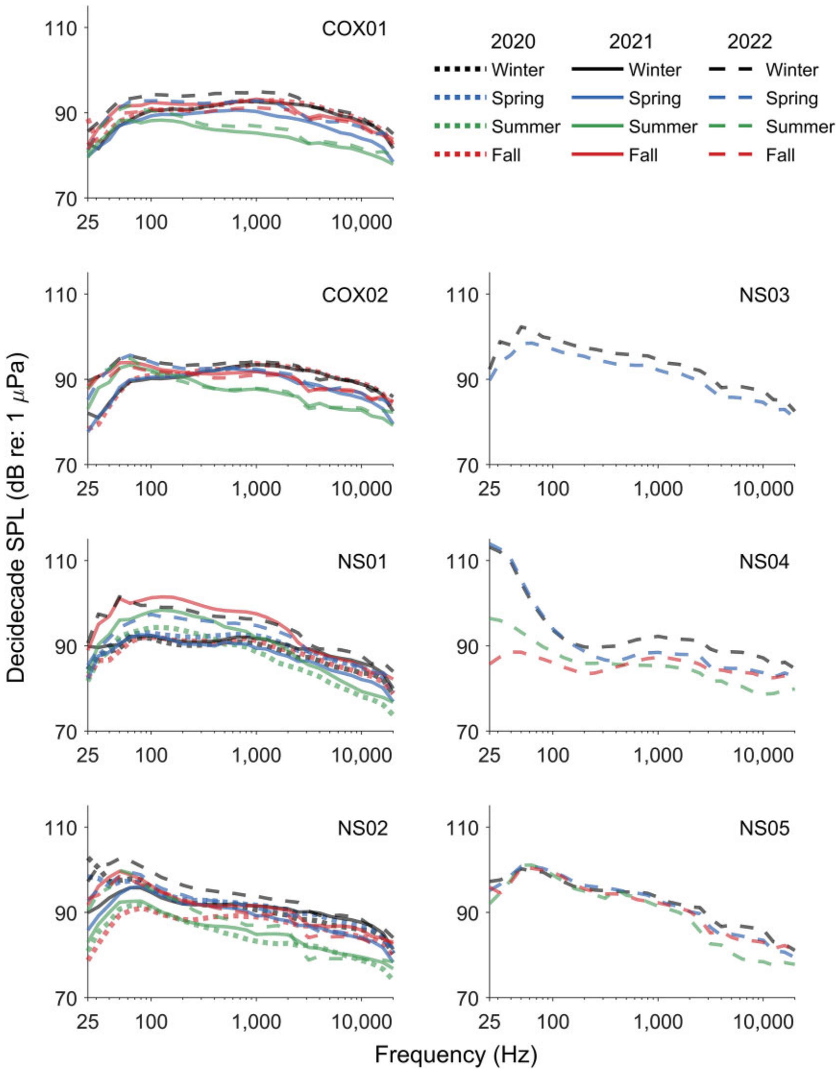

Figure 7. Median seasonal, decidecade sound pressure levels (dB re 1 μPa) at sites COX01, COX02, NS01, NS02, NS03, NS04, and NS05 in 2020, 2021, and 2022, in the southern New England offshore wind energy area, depicting median amplitude as a function of frequency and season.

energy area development will both increase underwater noise levels as well as augmenting the risk of vessel strike (e.g. Van Der Hoop *et al.*, 2012; Conn and Silber, 2013). Wind energy area development will introduce a wide range of vessel traffic from survey vessels, crew transfer vessels to service operational vessels with estimates varying by lease site (see National Marine Fisheries Service Endangered Species Act Section 7 Biological Opinion, 2021 as an example). With nine current wind energy leases to be developed in the southern New England region, it will become an area of high vessel traffic particularly during the construction phase.

Ambient sound levels were higher in annual median, broadband SPLs between 2020 and 2022 across three (NS01, NS02, and COX02) of the four sites where recordings were 2 or more years in duration. Daily increases and broader periods of above median levels occurred from late 2021 into early 2022 at the same three locations with slight decreases during the summer months. Site COX01 yielded the most predictable cyclical pattern with high SPLs in winter and low SPLs in summer, which may be more indicative of a system affected by environmental variables, such as wind, waves, and temperature, rather than anthropogenic and biological signals (Buscaino *et al.*, 2016; Haver *et al.*, 2018). It is important to note that wind energy activities prior to construction can be extensive and range across a wide spectrum from airguns, high-resolution geophysical sources (e.g. multibeam echosounders, side scan sonars, sub bottom profilers, boomers, and sparkers), oceanographic instrumentation (e.g. acoustic doppler current profilers, split-beam fisheries sonars), and communication/tracking sources (e.g. acoustic releases and locators, navigational transponders) (Ruppel *et al.*, 2022). With wind energy construction starting spring 2023 in two of the nine wind energy areas of the southern New England region, extensive preparatory surveys have already been underway. Therefore, further examination of the potential contribution of these other sources used within the wind energy area over this 2 year period is essential in order to better understand the origins of this increase in ambient sound levels. Some of the highest SPLs were observed in the first half of data at NS04 in 2022 and were anthropogenic in nature but inconsistent with normal vessel operation. Thus, further work needs to be conducted to assess whether increases in SPLs during this time period at NS04 resulted from fishing activity, preparatory work by wind energy developers, or some other anthropogenic source.

Broadband and decidecade SPLs trended higher in winter and early spring months compared to summer months; however, this trend diminished from mid-2021 onwards at NS01 and NS02 and suggests that changes in sound inputs may have occurred from then onward. While weather and environmental properties certainly explain some of the seasonal and annual variability in received SPLs, anthropogenic, and biological sources can also contribute to broad observable patterns in soundscapes (Stanley *et al*., 2021; Warren *et al*., 2021). The increase in baleen whale presence outside of summer months conforms to increases in ambient sound at lower frequencies, yet as with vessels it was difficult to isolate as a causal driver of ambient SPLs.

This study provides a broad baseline understanding of the species, ambient sound levels, and vessel activity within the soon to be developed southern New England wind energy area. They show that this is a biologically important area for a multitude of cetaceans and is subject to considerable vessel noise. These data will allow for changes to be measured throughout the periods of wind energy area construction across all nine lease areas as well as during the wind farms operational period. Similar approaches in other wind energy areas is essential if we want to be able to assess effects, both positive and negative, of this significant development across the US eastern seaboard.

Animal ethics and welfare

There are no animal ethics and welfare concerns.

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Supplementary data

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

Tables S1 and S2 present the annual and cumulative (i.e. across all available data) statistics of 1-min broadband and decidecade sound pressure levels, respectively, at each recording site (NS01–05 and COX01–02) in the southern New England offshore wind energy area. Figure S1 depicts daily medians of broadband sound pressure levels, and Figure S2 presents median broadband sound pressure levels per month and per hour.

Author contributions

SMVP was responsible for the study design, conceptual development, and writing of the manuscript; AID was responsible for data analysis and oversight of the odontocete analyses and manuscript writing; TA was responsible for data analysis of minke whales and reviewing the manuscript; RG was responsible for data analysis of the vessel data and writing of the manuscript; AH was responsible for data analysis of the harbour porpoise and delphinid data, and writing of the manuscript, JAM was responsible for data analysis of the vessel, oversight and writing of the manuscript; XM was responsible for writing the minke whale automated software, data analysis, and review of the manuscript; TJR was responsible for data analysis of the ambient sound metrics and writing of the manuscript; ST was responsible for data analysis of the baleen whales and reviewing of the manuscript; AW was responsible for data analysis of the sperm whale data and writing of the manuscript; GED was responsible for data analysis and oversight of the baleen whale data, and writing of the manuscript.

Conflict of interest

The authors declare no conflicts of interest.

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Data availability

As 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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