



# Cetacean acoustic occurrence on the US Atlantic Outer Continental Shelf from 2017 to 2020

Katie A. Kowarski<sup>1</sup>  | S. Bruce Martin<sup>1</sup> | Emily E. Maxner<sup>1</sup> |  
Carmen B. Lawrence<sup>1</sup> | Julien J.-Y. Delarue<sup>1</sup> |  
Jennifer L. Miksis-Olds<sup>2</sup> 

<sup>1</sup>JASCO Applied Sciences, Dartmouth, Nova Scotia, Canada

<sup>2</sup>University of New Hampshire, Durham, New Hampshire

## Correspondence

Katie Kowarski, 20 Mount Hope Avenue,  
Dartmouth, Nova Scotia B2Y 4S3, Canada.  
Email: [katie.kowarski@jasco.com](mailto:katie.kowarski@jasco.com)

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## Abstract

Long-term distribution data for cetaceans are lacking, inhibiting the ability of management bodies to assess trends and react appropriately. Such is true even along the US Atlantic Outer Continental Shelf (OCS) where previous passive acoustic monitoring programs have laid the groundwork for monitoring cetacean occurrence over a multidecadal scale. Here, we continue and expand the scope of previous acoustic programs, providing a synopsis of the monthly cetacean acoustic occurrence from late 2017 to late 2020. Acoustic data were collected using bottom-mounted autonomous recorders located at seven stations along the OCS in depths of 212–900 m. Automated cetacean vocalization detector-classifiers were applied, and the resulting automated detections directed the manual review of a subset of the data by analysts. Only manual detections informed the occurrence results. Six baleen whale species and at least eight toothed whale species occurred in the region with diversity increasing in winter. In considering previous monitoring program results, we found evidence that some mysticete whales are spending less time in the region annually, confirmed that some species

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occur farther offshore than previously reported, and identified two previously unreported areas utilized by beaked whales. For effective species management, these findings must be considered, and monitoring programs continued.

#### KEYWORDS

Atlantic Ocean, baleen whale, beaked whale, cetaceans, distribution, dolphin, mysticete, odontocete, outer continental shelf, passive acoustic monitoring

## 1 | INTRODUCTION

Long-term trend analysis is necessary to assess changes in population distribution, habitat use, and extinction risk and has therefore become a cornerstone of conservation biology. Management organizations, for example, the International Union for Conservation of Nature (IUCN), rely on long-term monitoring data (e.g., minimum requirements include 10 years or three generations) to assess whether populations and species will be listed (International Union for Conservation of Nature, 2021). For some taxa, such as birds, due to consistency in funding, accessibility of animals, and affordable monitoring equipment, reliable data can be available over many decades and trends can be accurately observed and appropriate management measures implemented (Margalida, 2017). For marine mammal populations, particularly cetaceans, long-term trend information is often lacking, hindering assessment efforts. Here, we aim to contribute to the long-term understanding of cetacean occurrence on the US Atlantic Outer Continental Shelf (OCS).

Cetaceans can be long-lived (some exceeding 100 years) (e.g., Keane et al., 2015); therefore, research on a decadal scale is required for these animals, which are inherently challenging to monitor. Whale and dolphin surveys from vessel or aircraft platforms are expensive (and unsustainable in the long-term for many research groups) and are limited temporally, being relatively short duration and only capturing a season of the year when animals are present (due to migration) or when weather and sea state allows (Mellinger et al., 2007). Shore-based surveys are only appropriate in some areas and for inshore species. Visual survey techniques can be limited due to visibility (e.g., fog, daylight) and are constantly impaired by the very nature of aquatic animals spending most of the time submerged (Mellinger et al., 2007).

Passive acoustic monitoring (PAM) via autonomous recorders presents an opportunity for sustainable, year-round, long-term, multispecies, cetacean monitoring and has been used to inform the assessment of populations (Committee on the Status of Endangered Wildlife in Canada, 2019). Many cetaceans produce sounds regularly (some species show diel or seasonal variations) that can be classified with some confidence to the species level, making them appropriate candidates for PAM monitoring (e.g., Español Jiménez & van der Schaar, 2018; Leroy et al., 2016; Risch et al., 2019). Acoustic recorders near the seabed can collect data in remote marine locations for years, monitoring passively for vocalizing animals, without regard for weather, daylight, season, or sea state (Mellinger et al., 2007). PAM is limited to monitoring vocally active animals within the detection range of the recorder (which dynamically changes as a function of ambient sound related to local weather, sea state, and anthropogenic activity) whose vocalizations fall within the frequency range of the recorder's audible bandwidth.

The eastern seaboard of the United States is home to a diverse group of cetacean species, and the area has a history of long-term PAM programs that described the acoustic occurrence of many of them. Risch et al. (2014a) described the seasonal migration of minke whales (*Balaenoptera acutorostrata*) from 2004 to 2012. Davis et al. (2017, 2020) described the changes in distribution of North Atlantic right whales (*Eubalaena glacialis*) and the acoustic occurrence of humpback (*Megaptera novaengliae*), sei (*Balaenoptera borealis*), fin (*Balaenoptera physalus*), and blue whales (*Balaenoptera musculus*) from 2004 to 2014. An acoustic data set spanning 2011 to 2015 was used to assess the distribution of northern bottlenose whales (*Hyperoodon ampullatus*), Cuvier's (*Ziphius cavirostris*),

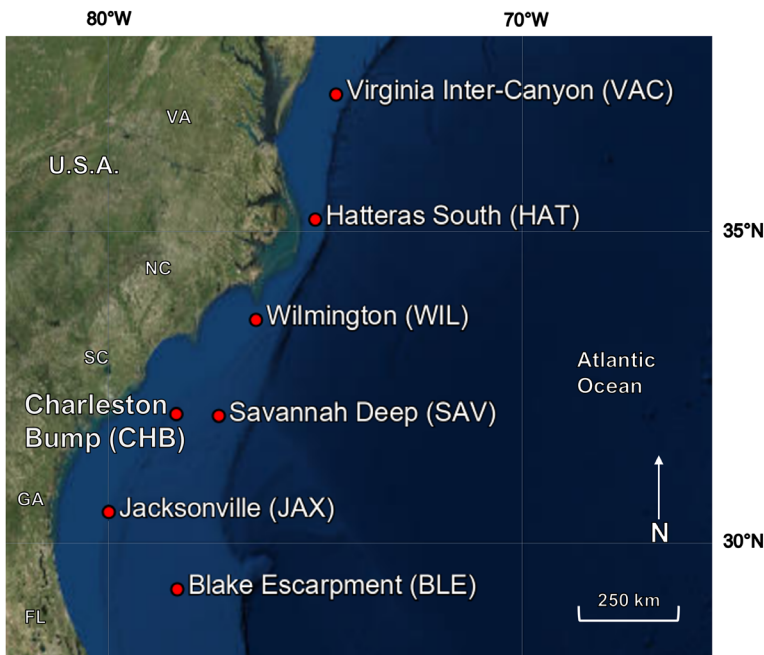
Sowerby's (*Mesoplodon bidens*), Gervais' (*Mesoplodon europaeus*), and Blainville's (*Mesoplodon densirostris*) beaked whales (Stanistreet et al., 2017), and sperm whales (*Physeter macrocephalus*; Stanistreet et al., 2018). Pygmy (*Kogia breviceps*) and dwarf (*Kogia sima*) sperm whale acoustic occurrence was described from 2011 to 2015 (Hodge et al., 2018) and odontocete click occurrence was investigated from 2016 to 2019 (Cohen et al., 2022). These impressive PAM programs have provided unprecedented and significant information on the distribution of marine mammals off the US eastern seaboard. Though the data sets are long-term in the context of cetacean research, the monitoring periods are short relative to what is ideal for species trend analysis and subsequent risk assessment by management bodies. Especially where shifts in distribution have already been observed (Davis et al., 2017, 2020), monitoring of the region must continue, and reporting should be expanded.

This article provides an updated synopsis of the monthly acoustic occurrence of cetacean species on the US Atlantic OCS from 2017 to 2020, describing areas both within and beyond the scope of previous PAM programs. Acoustic data were collected as part of the Atlantic Deepwater Ecosystem Observatory Network (ADEON; <https://adeon.unh.edu/>), which took an all-species approach to understanding ecosystem health. Our findings can be used in conjunction with previous PAM programs to interpret long-term trends in cetacean distribution and occurrence.

## 2 | METHODS

### 2.1 | Data collection

Underwater acoustic data were collected at seven stations (Figure 1) from late 2017 to late 2020 (Table 1). Autonomous Multichannel Acoustic Recorders (AMARs; JASCO Applied Sciences) were incorporated into Autonomous Long-Term Observatory (ALTO) landers (see Miksis-Olds et al., 2021) that sat on the seafloor at depths of 212–900 m. The landers were replaced every 5–12 months, resulting in four recording periods: November/December 2017 to June



**FIGURE 1** Location of acoustic recording stations on the Outer Continental Shelf along the US east coast. Map obtained from JASCO's Ark software.

**TABLE 1** The locations, dates, and water depth for acoustic recorders deployed at the seven stations on the Atlantic Outer Continental Shelf during four recording periods spanning 3 years. Equipment was replaced every 5–12 months; these timeframes are referred to as recording periods and are associated with the deployment and retrieval of equipment.

Station	Recording period	Deployed	Retrieved	Latitude (° N)	Longitude (° W)	Water depth (m)
VAC	1	Nov 22, 2017	Dec 11, 2017	37.24618	74.51392	213
	1b	Dec 10, 2017	Jun 20, 2018	37.24631	74.51350	212
	2	Jun 20, 2018	Nov 12, 2018	37.24603	74.51437	212
	3	Nov 12, 2018	Jul 7, 2019 <sup>a</sup>	37.24603	74.51453	212
	4	Oct 21, 2019	Jul 1, 2020 <sup>a</sup>	37.21000	74.51850	257
HAT	1	Nov 24, 2017	Jun 18, 2018	35.19955	75.02038	296
	2	Jun 18, 2018	Nov 11, 2018	35.19978	75.02042	294
	3	Nov 11, 2018	Oct 23, 2019	35.19992	75.01978	291
	4	Oct 23, 2019	Nov 27, 2020	35.19918	75.02062	294
WIL	1	Nov 26, 2017	Jun 15, 2018	33.58523	76.45056	461
	2	Jun 15, 2018	Nov 10, 2018	33.58607	76.45075	456
	3	Nov 10, 2018	Oct 24, 2019	33.58545	76.45057	460
	4	Oct 24, 2019	Nov 28, 2020	33.58500	76.45058	464
CHB	1	Dec 3, 2017	Jun 13, 2018	32.07024	78.37405	404
	2	Jun 13, 2018	Nov 4, 2018	32.07050	78.37407	404
	3	Nov 4, 2018	Oct 30, 2019	32.07052	78.37373	401
	4	Oct 31, 2019	Dec 4, 2020	32.07015	78.37403	415
SAV	1	Nov 27, 2017	Jun 14, 2018	32.04218	77.34790	790
	2	Jun 14, 2018	Nov 8, 2018	32.04205	77.34762	792
	3	Nov 8, 2018	Oct 25, 2019	32.04280	77.34808	790
	4	Oct 24, 2019	Nov 29, 2020	32.04192	77.34758	814
JAX	1	Dec 1, 2017	Jun 12, 2018	30.49274	80.00312	317
	2	Jun 12, 2018	Nov 7, 2018	30.49302	80.00288	318
	3	Nov 7, 2018	Nov 17, 2019	30.49312	80.00295	317
	4	Jan 12, 2020	Dec 13, 2020	30.49492	80.00243	324
BLE	1	Nov 29, 2017	Jun 10, 2018	29.25098	78.35075	872
	2	Jun 10, 2018	Nov 6, 2018	29.25115	78.35012	867
	3	Nov 6, 2018	Nov 16, 2019	29.25060	78.35107	868
	4	Oct 28, 2019	Dec 2, 2020	29.25115	78.35037	900

<sup>a</sup>Not retrieved as planned, it was instead brought to surface by a fishing trawler and returned to JASCO.

2018 (recording period 1), June 2018 to November 2018 (recording period 2), November 2018 to October/November 2019 (recording period 3), and October 2019/January 2020 to November/December 2020 (recording period 4) (Table 1). The exception was the AMAR at Virginia Inter-Canyon (VAC), which was additionally replaced during recording period 1 after a single month had passed (recording period 1b in Table 1) to allow assessment of equipment performance to ensure the lander design did not require adjustment before the second recording period. In recording period 4, VAC was moved 4 km south in an effort to reduce interactions with fishing gear. Despite these efforts to avoid interactions, the lander at VAC was either hit by fishing gear or retrieved early by fishers each year.

Each bottom lander was equipped with four hydrophones and was designed to accomplish several goals for the ADEON project. Both low (8 or 16 kHz) and high (375 or 512 kHz) sampling rate data from a single hydrophone on

each lander were utilized for marine mammal acoustic occurrence analysis (Table 2). To address a multitude of research questions, the ADEON acoustic recording schedules were complex in that there were four unique recording regimes (in terms of duration, channel, sampling rate, and sleep mode) within a single recording cycle, and these regimes varied across recording periods. Complete information on data collection, recording schedules, and the bottom lander platform can be found at <https://adeon.unh.edu/>. Here, we provide simplified recording schedule summaries that are limited to the data used for the present marine mammal analysis (Table 2). The raw acoustic recordings from ADEON are available to researchers through the National Centers for Environmental Information (NCEI; <https://ncei.noaa.gov>). Processed soundscape data, hourly mammal acoustic presence data, and visual marine mammal sightings data are available from the ADEON website (see <https://adeon.unh.edu/>).

## 2.2 | Data analysis

Acoustic data were analyzed for the occurrence of marine mammal acoustic signals using a combination of automated and manual techniques. Output from automated detectors directed the manual analysis, but automated

**TABLE 2** Equipment and recording schedule for data used during marine mammal analysis. “NA” indicates that no acoustic data were collected.

Specification	Recording period				
	1	1b (VAC)	2	3	4
AMAR model <sup>e</sup>	G3	G3	G3	G4	G4
Hydrophone model <sup>c</sup>	M36-V35dB omnidirectional	M20 directional	M36-V35dB omnidirectional	M36-V35dB omnidirectional	M36-V35dB omnidirectional
Hydrophone sensitivity (dB re 1 V/ $\mu$ Pa)	$-165 \pm 3^a$	-180	$-165 \pm 3^a$	$-165 \pm 3^a$	$-165 \pm 3^a$
Bit depth	24 bit and 16 bit <sup>f</sup>	24 bit	24 bit and 16 bit <sup>f</sup>	24 bit	24 bit
Gain (dB)	6 <sup>b</sup>	6 <sup>b</sup>	6 <sup>b</sup>	13	13
Recording cycle duration (min)	21	17	60	60	60
High sampling rate (kHz)	375	NA	375	512	512
High sampling rate recording schedule (min) <sup>d</sup>	1 on, 21 off	NA	1 on, 19 off, 1 on, 19 off, 1 on, 19 off	1 on, 9 off, 1 on, 9 off, 1 on, 9 off, 1 on, 9 off, 1 on, 5 off, 1 on, 13 off	1 on, 9 off, 1 on, 9 off, 1 on, 9 off, 1 on, 9 off, 1 on, 5 off, 1 on, 13 off
Low sampling rate (kHz)	8	8	8	16	16
Low sampling rate recording schedule (min) <sup>d</sup>	11 on, 10 off	5 on, 12 off	19 on, 1 off, 19 on, 21 off	9 on, 11 off, 9 on, 31 off	9 on, 11 off, 9 on, 31 off

<sup>a</sup>10–150000 Hz.

<sup>b</sup>Applied to low sampling rate (8 kHz) data only.

<sup>c</sup>GeoSpectrum Technologies Inc.

<sup>d</sup>“On” indicates recording duration and denotes the data used for marine mammal analysis. “Off” indicates recording interval and denotes times where the recorder was recording a different sampling rate, channel, duration, or was in sleep mode.

<sup>e</sup>The generation 4 (G4) AMAR is different from the generation 3 (G3) AMAR in that it is capable of recording at a higher sampling rate and has greater memory storage. Details on the specifications of these AMAR models can be found at <https://jasco.com>.

<sup>f</sup>24 bit for data sampled at 8 kHz and 16 bit for data sampled at 375 kHz.

detections were not included in the final occurrence results, which are based only on manual marine mammal detections from analysts. The analysis occurred in four stages.

In stage 1, a suite of automated detector-classifiers (henceforth referred to as automated detectors) were applied to the acoustic data. Three types of automated detectors were applied: an odontocete click detector, a tonal contour detector, and a pulse train detector. The automated odontocete click detector (1) used a Teager-Kaiser energy detector to identify possible click events, (2) extracted zero-crossing characteristics of the detection, (3) compared the detection characteristics to a library of species-specific zero-crossing click characteristic templates, and (4) classified the detection as the species with the lowest Mahalanobis distance (for full details, see Kowarski, Delarue, et al., 2018). Twelve species (or species groups) were targeted by the automated click detector (Table 3). The automated tonal contour detector (1) identified contours of elevated energy, (2) extracted contour characteristics, (3) compared the contour characteristics to a library of species-specific contour templates, and (4) classified the contour as any species template it fell within (for full details see Kowarski, Evers, et al., 2018, Kowarski et al., 2020). Eight species (or species groups) were targeted by the automated tonal contour detector (Table 3). The automated pulse train detector expanded upon the contour detector by searching for contour detections that occurred in sequence that matched a template. This pulse train detector was used to identify potential minke whales (Table 3). The odontocete click detector was applied to the high sampling rate data (375 and 512 kHz data), while the tonal contour detector and pulse train detector were applied to the low sampling rate data (8 and 16 kHz data).

In stage 2, the Automated Data Selection for Validation algorithm (ADSV; Kowarski, Delarue, et al., 2021) was applied. ADSV used three descriptors of the results from the combination of all automated detectors to select a subset of approximately 0.5% (over 400 hr) of the data for manual validation. The three descriptors were: (1) Diversity, the number of triggered automated detectors per file; (2) Counts, the number of automated detections per automated detector in each file; and (3) Temporal Distribution, the distribution of detections for each automated detector throughout the recording period. The aim of ADSV is to produce a subset where the distribution of the three descriptors is as similar as possible to that of the original full data set (see example in Figure S1). ADSV was applied separately to each station, sampling rate, and recording period.

In stage 3, the data selected via ADSV were manually reviewed by experienced analysts through visual and aural review of spectrograms using PAMlab (JASCO Applied Sciences), and the acoustic presence of all species known to potentially occur in this region was determined. Low sampling rate data (8 and 16 kHz data) were analyzed for the occurrence of baleen whales, the whistles of pilot and killer whales, and the low-frequency sounds of dolphins (Simard et al., 2011). The high sampling rate data (375 and 512 kHz data) were analyzed for the occurrence of oceanic dolphin whistles and the clicks of delphinids, beaked whales, sperm whales, harbor porpoises, and *Kogia* spp. Each file reviewed was analyzed for the occurrence of any cetacean signal, regardless of whether the automated detector for that species was triggered in the file. Manual analysts reviewed acoustic data for species-specific signals targeted by automated detectors (Table 3) as well as any other previously described vocalization types including the codas, creaks, and slow clicks of sperm whales (Gero et al., 2016; Madsen et al., 2002b), arch calls, D calls, and blurps of blue whales (Berchok et al., 2006; Mellinger & Clark, 2003), the 40 Hz pulses of fin whales (Delarue, 2008), the downsweeps of minke whales (Edds-Walton, 2000), the tonal calls and gunshots of north Atlantic right whales (Parks et al., 2019), and the quick, narrowband downsweeps of sei whales (Tremblay et al., 2019).

During manual review, all available information including spectral characteristics, time of year, and location was considered when assigning an acoustic signal to a species. For odontocete clicks, a click train containing at least three clicks had to be present. The main identifying characteristics of odontocete clicks were the shape of the waveform, center frequency, interpulse-interval (IPI), duration, bandwidth, and whether there was a frequency-modulated upsweeping slope indicative of a beaked whale. For baleen whales, analysts not only considered the duration, frequency, and shape of individual signals, but also whether the signals occurred in any apparent patterns indicative of songs, which are species-specific. Recent manual detections of other species were also a consideration during analysis, particularly where overlapping repertoires makes species differentiation difficult. For example, North Atlantic right whales produce upcalls, but this is also a signal that can be incorporated into humpback whale song (Davis

**TABLE 3** The cetacean acoustic signals targeted by automated detectors.

Species	Automated detector	Acoustic signal targeted by automated detector
Harbor porpoise ( <i>Phocoena phocoena</i> )	Odontocete click detector	Narrowband high-frequency click (e.g., Villadsgaard et al., 2007)
Kogiids ( <i>Kogia breviceps</i> , <i>Kogia sima</i> )	Odontocete click detector	Narrowband high-frequency click (e.g., Hildebrand et al., 2019; Merkens et al., 2018)
Sperm whale ( <i>Physeter macrocephalus</i> )	Odontocete click detector	Usual click (e.g., Madsen et al., 2002a; Møhl et al., 2003)
Dolphins ( <i>Lagenorhynchus acutus</i> , <i>Grampus griseus</i> , <i>Stenella frontalis</i> , <i>Tursiops truncatus</i> , <i>Stenella clymene</i> , <i>Lagenodelphis hosei</i> , <i>Stenella attenuata</i> )	Odontocete click detector	Impulsive click (e.g., Hamran, 2014)
	Tonal contour detector	Whistle and low-frequency sounds (e.g., Simard et al., 2011; Simões Amorim et al., 2019)
Pilot whale ( <i>Globocephala melas</i> , <i>Globicephala macrorhynchus</i> )	Odontocete click detector	Echolocation click (e.g., Eskesen et al., 2011)
	Tonal contour detector	Whistle (e.g., Nemiroff & Whitehead, 2009; Van Cise et al., 2018)
Killer whale ( <i>Orcinus orca</i> , <i>Pseudorca crassidens</i> )	Odontocete click detector	Echolocation click (e.g., Eskesen et al., 2011)
	Tonal contour detector	Whistle (e.g., Rendell et al., 1999; Thomsen et al., 2001)
Cuvier's beaked whale ( <i>Ziphius cavirostris</i> )	Odontocete click detector	Frequency-modulated upsweeping click (e.g., Baumann-Pickering et al., 2013; Zimmer et al., 2005)
Blainville's beaked whale ( <i>Mesoplodon densirostris</i> )	Odontocete click detector	Frequency-modulated upsweeping click (e.g., Baumann-Pickering et al., 2013; Johnson et al., 2004)
Gervais' beaked whale ( <i>Mesoplodon europaeus</i> )	Odontocete click detector	Frequency-modulated upsweeping click (e.g., Baumann-Pickering et al., 2013; Gillespie et al., 2009)
Northern bottlenose whale ( <i>Hyperoodon ampullatus</i> )	Odontocete click detector	Frequency-modulated upsweeping click (e.g., Clarke et al., 2019)
Sowerby's beaked whale ( <i>Mesoplodon bidens</i> )	Odontocete click detector	Frequency-modulated upsweeping click (e.g., Clarke et al., 2019)
True's beaked whale ( <i>Mesoplodon mirus</i> )	Odontocete click detector	Frequency-modulated upsweeping click (e.g., DeAngelis et al., 2018)
Blue whale ( <i>Balaenoptera musculus</i> )	Tonal contour detector	A and B note (e.g., Mellinger & Clark, 2003)
Fin whale ( <i>Balaenoptera physalus</i> )	Tonal contour detector	20 Hz pulse and 130 Hz upsweep (e.g., Delarue et al., 2009)
Humpback whale ( <i>Megaptera novaengliae</i> )	Tonal contour detector	Moans (incorporated in both songs and nonsongs) (e.g., Dunlop et al., 2008; Payne & McVay, 1971)
Minke whale ( <i>Balaenoptera acutorostrata</i> )	Pulse train detector	Pulse train (e.g., Risch et al., 2014b)
North Atlantic right whale ( <i>Eubalaena glacialis</i> )	Tonal contour detector	Upcall (e.g., Parks et al., 2019)
Sei whale ( <i>Balaenoptera borealis</i> )	Tonal contour detector	Broadband downsweep (e.g., Nieuwkerk et al., 2020)

et al., 2017). Upcalls (upsweeping moans from approximately 90 to 200 Hz over 0.5–2 s) were only considered right whale if there was not a humpback whale confirmed or suspected within 2 hr or if it cooccurred with a right whale gunshot. Similarly, fin, blue, and sei whales all produce downsweeping moans from approximately 100 to 30 Hz (Baumgartner et al., 2008; Berchok et al., 2006; Delarue, 2008; Mellinger & Clark, 2003; Nieu Kirk et al., 2020; Romagosa et al., 2021; Širović et al., 2013). These downsweeps were considered sei whale if they occurred in a set of 2–4 with an interval of 3–4 s, fin whale if there were fin whale 20 Hz pulses confirmed within 1 hr but no sei or blue whales confirmed or suspected, and blue whale if it was more than 2 s long. We took a conservative approach to analysis, where any uncertainty in species identification, either due to a faint signal or nonspecies-unique signal, was considered a “possible” manual detection. Possible detections were not included in the monthly occurrence results but were summarized in Tables S1–S12.

In some instances, overlapping repertoires across species made it difficult for analysts to classify vocalizations to the species level. To manage this, broader species categories were applied when necessary. Gervais' and True's beaked whales overlap in both spatial distribution and echolocation click repertoire (DeAngelis et al., 2018; MacLeod et al., 2006). Clicks matching the characteristics of these two species were categorized as “Gervais/True's beaked whales.” Pygmy and dwarf sperm whales have narrow-band high-frequency (NBHF) clicks that could not be differentiated from each other or those of harbor porpoise. Clicks matching the characteristics of these three species were categorized as NBHF.

Delphinids were particularly challenging given their wide overlapping distributions and repertoires. Two categories were applied for delphinids: “dolphins” and “pilot/killer whales.” Acoustic signals assigned as dolphins were whistles with most energy above 5 kHz, the low-frequency sounds of dolphins found primarily under 3 kHz (Simard et al., 2011), and clicks without a frequency-modulated upsweeping slope (indicative of beaked whales) that occurred between 20 and 100 kHz. The dolphin category is therefore very broad and may include small dolphins such as the Atlantic spotted, bottlenose, clymene, Fraser's, pantropical spotted, and/or Risso's dolphins as well as larger dolphins such as the false killer, killer, long-finned pilot, and short-finned pilot whales. Though pilot and killer whale clicks were captured under dolphins, an attempt was made to differentiate these species from smaller delphinids based on their tonal signals. Whistles with fundamental frequencies under 5 kHz were assigned to “pilot/killer whales.” This category is certainly a minimum estimate of occurrence as it does not capture periods when killer and pilot whales were clicking but not whistling.

In stage 4 of data analysis, additional manual review was completed to identify the signals of North Atlantic right whales. This targeted analysis was undertaken because this species is at risk, acoustically cryptic compared to its baleen whale counterparts, and was rarely detected using the ADSV methodology. Indeed, with only a 0.5% subset of the ADEON data manually analyzed, ADSV is expected to be less effective at identifying rare or cryptic species (Kowarski, Delarue, et al., 2021). Additional analysis was completed on the three most inshore stations Hatteras (HAT), Wilmington (WIL), and Jacksonville (JAX). These stations are the closest to known right whale habitat (Davis et al., 2017). For each detection event in the low sampling rate data sets, a file with the highest number of automated right whale upcall detections (tonal contour detector) was analyzed. A detection event was defined as automated right whale upcall detections occurring within one hour of each other where at least one file had three or more automated detections. By analyzing detection events instead of individual detections or files with detections, we aimed to increase the efficiency of analysis. For example, if a vessel was moving through the region and triggering the right whale automated detector for 2 hr, instead of checking the entire 2 hr of data, an analyst opened a single file, identified what was triggering the automated detector, and moved on to the next detection event. There is a chance a few upcalls would be missed amongst other sounds triggering the automated detector if it occurred outside of the file manually reviewed. JASCO's automated right whale upcall detectors have previously been found to have a high per call recall (e.g., 0.94 in Kowarski et al., 2020); therefore, by checking all automated detection events in addition to the ADSV methodology, we expect to capture almost all instances of right whale upcall occurrence.

The 0.5% ADSV subset of the full data set that was validated manually was selected to maximize validation within the fiscal and time constraints of the overall ADEON project. Nonetheless, our experience indicates that even



with only a portion of data reviewed, occurrence results can be reliable if necessary precautions are taken and caveats applied (Kowarski, Delarue, et al., 2021). Due to limited manual review, additional steps were taken to ensure the results included in this article are reliable. First, most data were reviewed by “senior” analysts with more than 5 years’ experience in marine mammal acoustic analysis, and when a less experienced analyst was employed, their work was reviewed by a senior analyst. Second, the performance of the automated detectors was quantified and can be found in the ADEON report (Miksis-Olds et al., 2021). Third, while the number of days per week with occurrence can be found for each species in the ADEON report (Miksis-Olds et al., 2021), here we provide a monthly presence/absence summary. By increasing the timeframe over which occurrence is presented, we reduce our chance for error. For example, if the analysis protocol caused the occurrence of a whale to be missed on a few days in October, it would not impact the results if the species was correctly identified in at least one instance in October. Given our protocol selected data for manual validation across all months of the year (Temporal Distribution descriptor of automated detector results), missing a species in an entire month is unlikely unless the animals were very rare or cryptic, hence the additional analysis for North Atlantic right whales. Fourth, and most significantly, because the automated detector performance varied across species (Kowarski, Delaure, et al., 2021; Miksis-Olds et al., 2021), this article only includes manually validated results and does not rely on the automated detectors. Indeed, while automation was used within the protocol to direct analysts to periods of potential cetacean presence, all findings and subsequent conclusions are based on detections made during manual review.

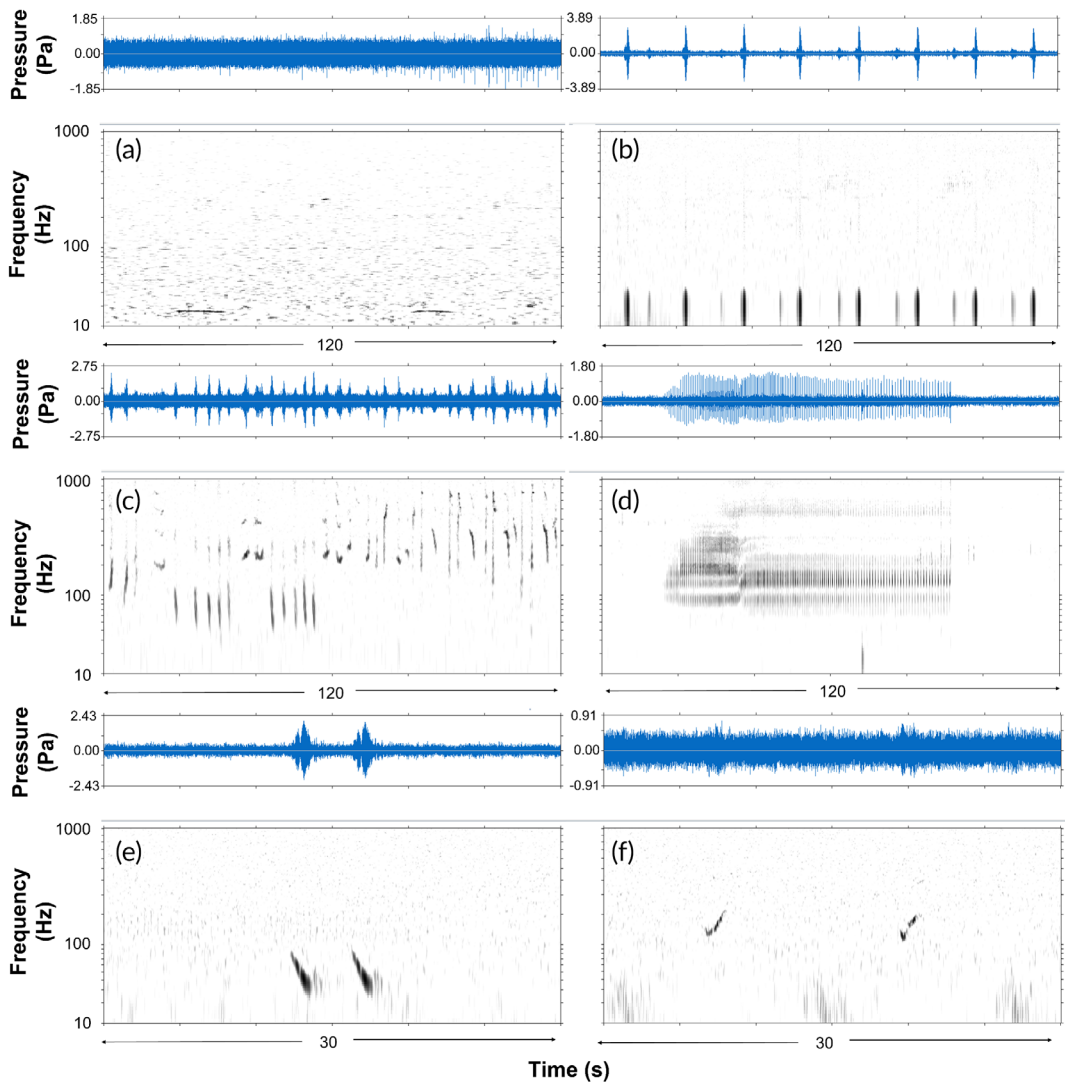
### 3 | RESULTS

ADEON was a large, multifaceted program that resulted in a total of 105.2 TB of acoustic data collected, a portion of which was collected for the purpose of cetacean acoustic occurrence analysis and was subsequently mined. Of the 82,562.62 hr of acoustic data mined (automated marine mammal vocalization detectors applied), 412.33 hr were manually reviewed for cetacean acoustic occurrence using the ADSV methodology. Acoustic files manually reviewed were distributed throughout the recording period (as defined by the Temporal Distribution descriptor of ADSV). On average, the acoustic files selected for manual review occurred across 6 days per month for the low sampling rate data and 12 days per month for the high sampling rate data. The fewer days, on average, with files analyzed per month for the low frequency data compared to high frequency data, reflects the longer duration of low frequency files (Table 2), resulting in fewer files selected by ADSV to reach 0.5% of the full data set. Six mysticete and at least eight odontocete acoustic signals were identified in the acoustic recordings (Figures 2–4). Audio clips of many of these signals can be found at <https://adeon.unh.edu/audiogallery>. Five or more species were commonly present in the same month at a station with species diversity increasing in winter when there was an increase in baleen whale acoustic presence (Figures 5 and 6).

Throughout the recording area, mysticete whale occurrence was largely seasonal with most occurring between fall and spring (Figure 5; September to June). Fin, blue, and humpback whales were more prevalent at the northern stations while sei and minke whales were more common at the southern stations (Figure 5).

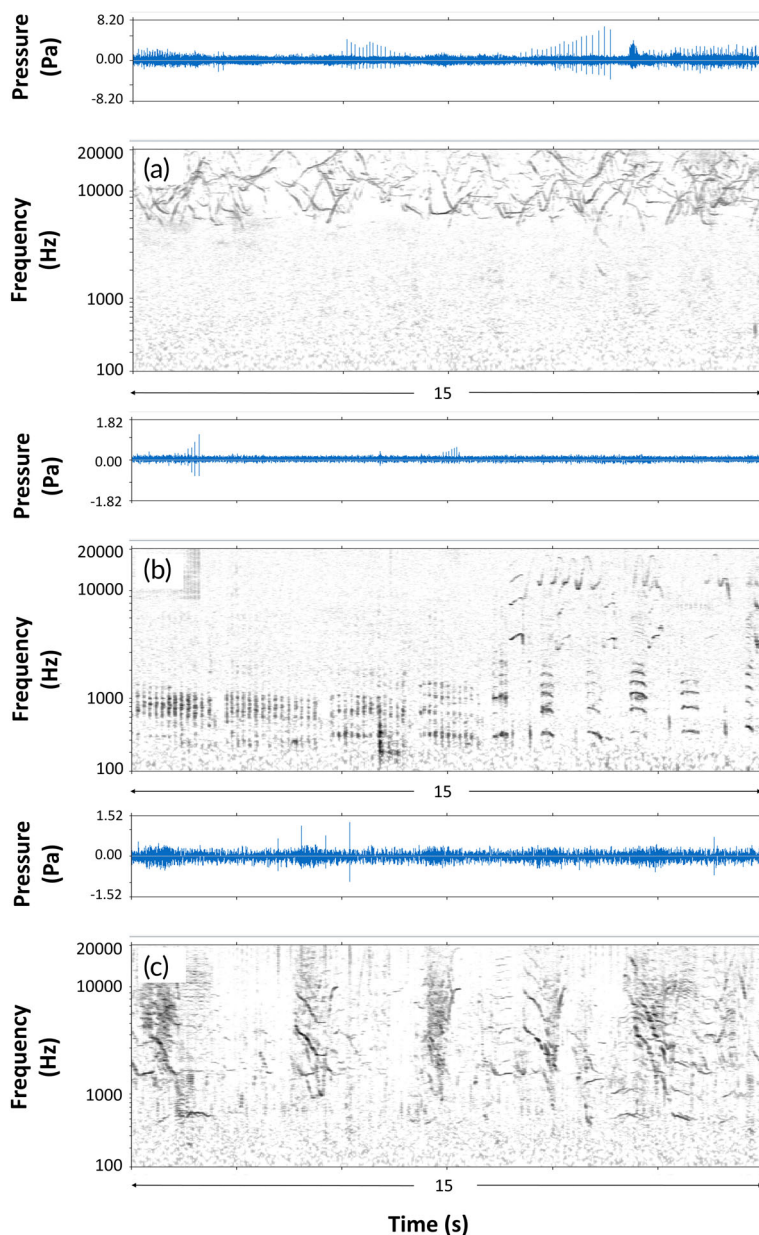
Analysts detected minke whale pulse trains, fin whale 20 Hz pulses, blue whale A notes, right whale upcalls, sei whale downsweeps, and humpback whale vocalizations (Figure 2). Most humpback whale manual detections were of songs (Figure 2), though nonsongs were identified in August and September at Blake Escarpment (BLE) and in April at VAC. The humpback whale song category included both full songs and song fragments as defined in Kowarski et al. (2019), and the nonsong category was defined as vocalizations not organized into phrases or subphrases. There were possible blue whale D call detections at HAT in March, and at VAC in January, May, June, and July. Possible fin whale 40 Hz call detections were made at VAC in April, May, and June.

In addition to the files selected for manual analysis using ADSV, 1265 low sampling rate files were analyzed for the occurrence of North Atlantic Right whale vocalizations. Upcalls were confirmed at HAT on January 29, 2018 (Figure 5). Additionally, possible detections were made in September at HAT; in June, July, August, and February at JAX; and in May, June, July, September, and December at WIL.



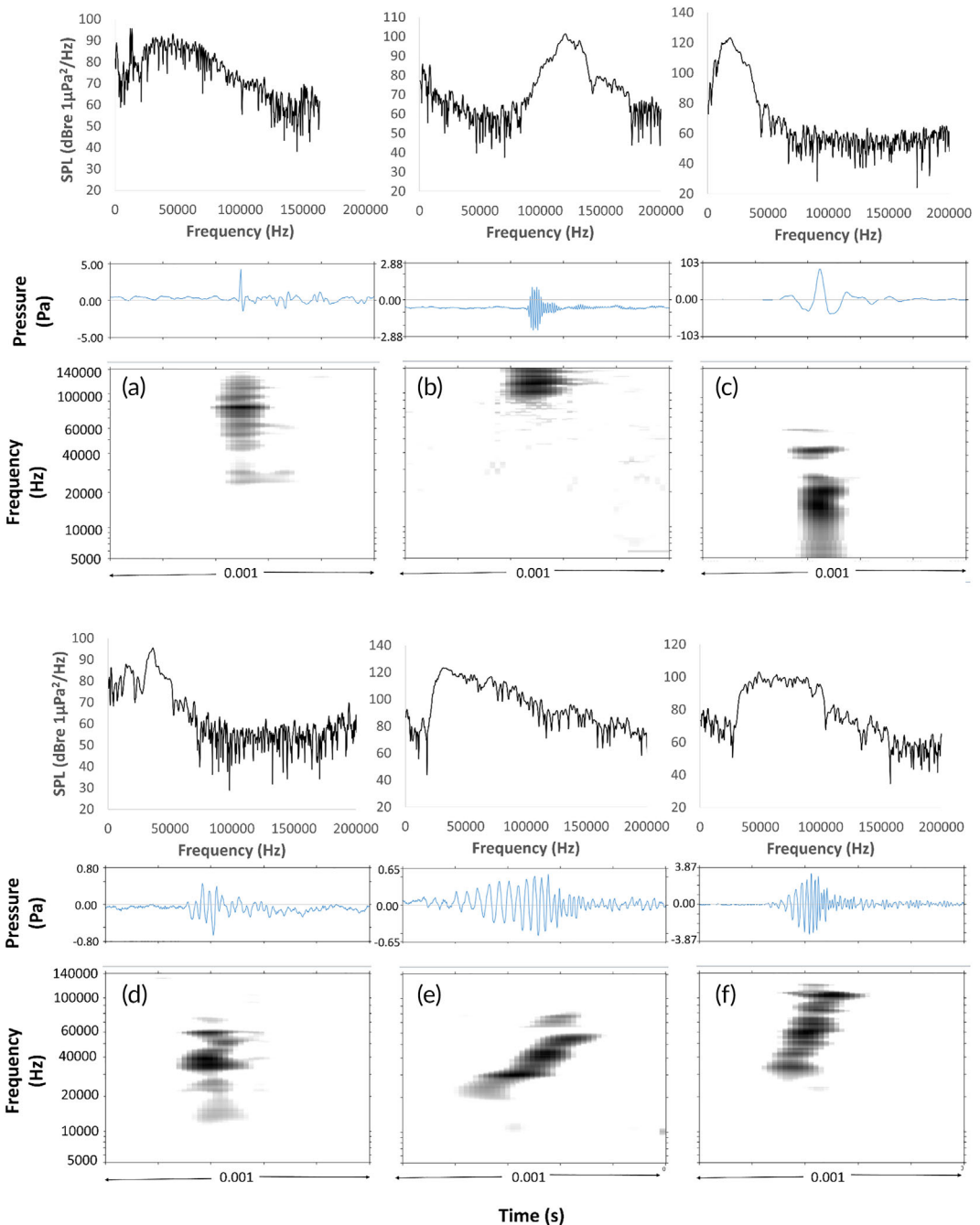
**FIGURE 2** Sound pressure waveforms (10–4,000 Hz) and spectrograms of mysticete acoustic signals identified in the data: (a) blue whale notes (horizontal lines at 17 Hz) recorded on March 17, 2020, at VAC; (b) fin whale 20 Hz pulses recorded on December 22, 2019, at VAC; (c) humpback whale song recorded on March 21, 2020, at VAC; (d) minke whale pulse train recorded on January 29, 2020, at WIL; (e) pair of sei whale downsweeps recorded on January 25, 2019, at BLE; and (f) right whale upcalls along with a distant seismic airgun survey visible under 50 Hz recorded on January 29, 2018, at HAT. Spectrogram parameters are: (a) 0.4 Hz frequency resolution (df) and 2 s time resolution (dt) of FFT with an overlap of 75%, Hamming window, normalized across time; and (b–f) 2 Hz frequency resolution (df), 0.125 s time resolution (dt) of FFT with an overlap of 75%, Hamming window, normalized across time. All spectrograms are log scale and span 10 Hz to 1 kHz.

NBHF clicks were absent at the northernmost VAC and HAT and more common at southern stations, occurring almost monthly at BLE (Figure 6). Vocalizations categorized as NBHF clicks, which may include dwarf sperm whale, pygmy sperm whale, and/or harbour porpoise vocalizations, were observed in nearly every month at BLE and Savannah (SAV), were common at WIL, were detected at Charleston Bump (CHB) in December, January, February, March, and April, and were detected in January at JAX. Sperm whale clicks were detected at all stations throughout the recording period, with a near monthly presence at northernmost VAC and southernmost BLE.

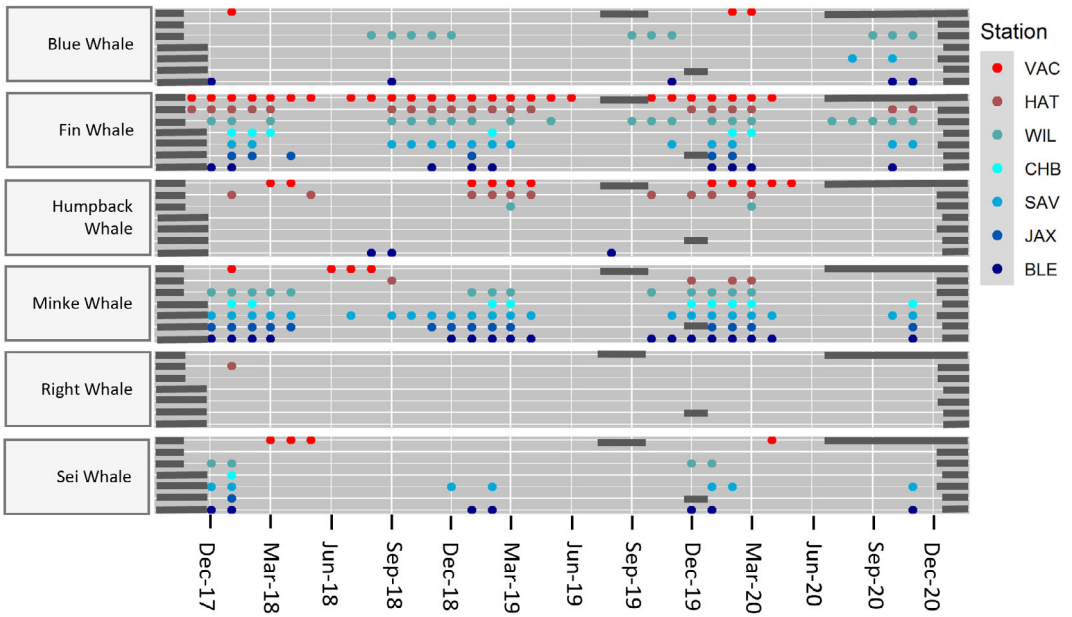


**FIGURE 3** Sound pressure waveforms (10–187,500 Hz) and spectrograms of delphinid tonal sounds identified in the data: (a) dolphin whistles (unknown species) recorded on June 25, 2018, at VAC; (b) low-frequency dolphin vocalizations recorded on November 29, 2017, at WIL with whistles also visible above 10 kHz; and (c) pilot/killer whale whistles recorded on April 6, 2019, at BLE. Spectrogram parameters are: log scale, 15 s duration, spanning 100 Hz to 20 kHz, 2 Hz frequency resolution (df) and 0.125 s time resolution (dt) of FFT with an overlap of 75%, Hamming window, normalized across time.

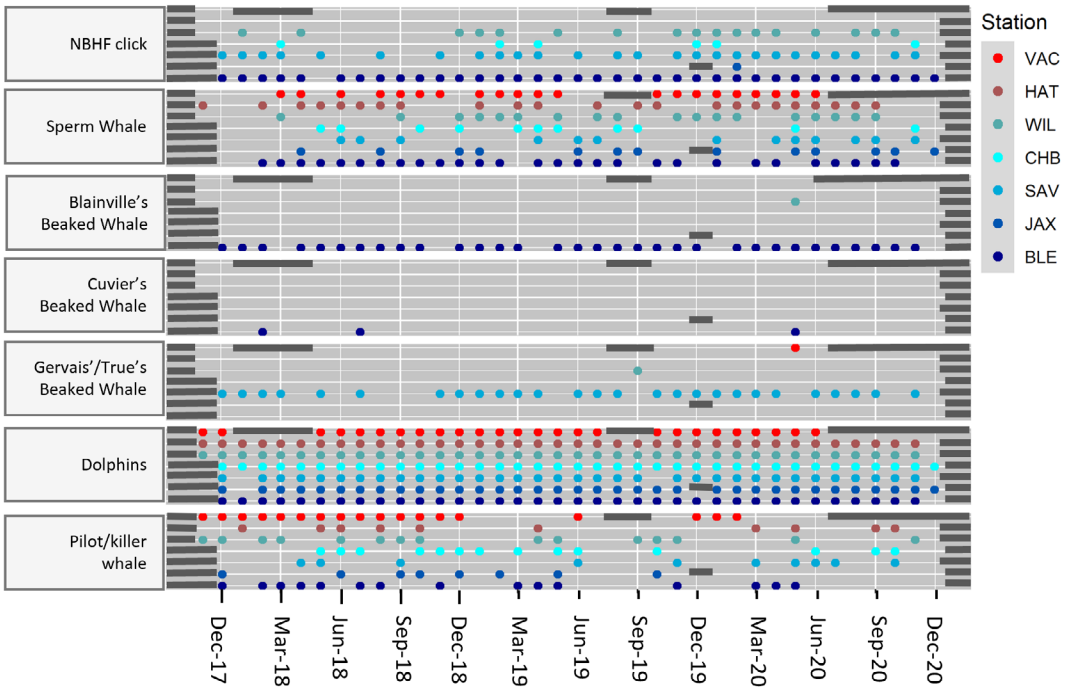
Beaked whale clicks (Figure 4) occurred throughout the year at SAV and BLE, in two instances at WIL, and one at VAC (Figure 6). All detections at SAV were assigned to Gervais'/True's beaked whales. Most detections at BLE were Blainville's beaked whale clicks, except for three that were Cuvier's beaked whales (Figure 6).



**FIGURE 4** Example power spectrum with sound pressure level (SPL) across frequencies, sound pressure waveforms (10–187,500 Hz), and spectrograms of odontocete clicks identified in the data: (a) delphinid click recorded on June 25, 2018, at VAC; (b) NBHF click recorded on January 15, 2019, at WIL; (c) sperm whale click recorded on November 5, 2019, at BLE; (d) Cuvier's beaked whale click recorded on May 29, 2020, at BLE; (e) Blainville's beaked whale click recorded on November 19, 2019, at BLE; (f) Gervais'/True's beaked whale click recorded on February 23, 2020, at SAV. Spectrogram parameters are: 0.001 s duration, spanning 5–140 kHz, 512 Hz frequency resolution (df) and 0.266 ms time resolution (dt) of FFT with an overlap of 92%, Hamming window, normalized across time.



**FIGURE 5** Presence of baleen whale vocalizations by month (MMM-YY) and station, with stations arranged north to south. Dark horizontal lines indicate times with no acoustic data.



**FIGURE 6** Presence of toothed whale vocalizations by month (MMM-YY) and station, with stations arranged north to south. Dark horizontal lines indicate times with no acoustic data.

Dolphins were the most prolific species group in the acoustic data, occurring in every station during almost every month (Figure 6). While the dolphin category included low-frequency sounds, whistles, and clicks, even if only restricted to whistles above 5 kHz (Figure 3), the presence results would go unchanged indicating dolphin occurrence is mostly that of small dolphins with high-frequency whistles, rather than the larger pilot and killer whale species, even though all groups produce similar clicks. Pilot/killer whale whistles (Figure 3) were identified sporadically at all stations during monitoring (Figure 6).

## 4 | DISCUSSION

A synopsis of monthly cetacean species diversity on the OCS off the eastern US from 2017 to 2020 has been provided. The acoustic presence of a species should not be interpreted as an animal in the immediate vicinity of the acoustic recorder. Detection ranges of animals are impacted by many factors including how loud the species is, how loud the environment is, the water depth, the depth of the animal, and the local topography. For example, off eastern Canada, Delarue et al. (2022) modeled the detection range of blue whale vocalizations to be from 6 to 200 km, depending on recording site. Such detection range modeling was beyond the scope of the present work, but it should be considered when interpreting results that detection ranges likely varied across time, space, and species. While presence was confirmed via manual analysis, an absence of acoustic detection in any given month does not necessarily indicate that the species was absent from the area. Animals may have been missed during data analysis (i.e., species vocalizations occurred outside of data recorded or manually reviewed, analysts missed faint signals, or faint signals were considered possible detections); they may have been present but not vocalizing; or their acoustic signals may have been beyond the detection range of the recorder. The impacts and rate of occurrence of these scenarios would vary across species and vocalization type. For example, the repertoires of most baleen whales (blue, fin, humpback, minke, and potentially sei whales) change seasonally, and they are more readily detected acoustically in fall and winter than in spring and summer (e.g., Leroy et al., 2016; Stanistreet et al., 2013). The impacts of missing an acoustic event were minimized by considering presence on a monthly basis; nonetheless, the results should be considered a minimum species occurrence. Here, we frame the cetacean occurrence results within the findings of previous large-scale PAM programs that occurred from 2004 to 2019 and included the US eastern seaboard.

### 4.1 | Blue whales

Blue whales were acoustically detected off Wilmington from August to December. In contrast, from 2004 to 2014 Davis et al. (2020) detected blue whale vocalizations in the same region (see region 10 in Davis et al., 2020) from late July to January. Further, a blue whale tagged in the Gulf of St. Lawrence, Canada in November 2014, reached the Wilmington area in January and proceeded back northward by February (Lesage et al., 2017). The more truncated seasonal occurrence off Wilmington observed here may be an artifact of our analysis method missing infrequent or faint vocalizations that occurred in July and January, months where Davis et al. (2020) detected signals on less than one day per week on average. Alternatively, these results may reflect blue whales arriving in the area later and leaving earlier in the season than in previous years. Davis et al. (2020) observed blue whales increasing time spent in northern latitudes and decreasing time spent in southern latitudes after 2010 for data that spanned 2004–2014. In 2015–2017, Delarue et al. (2022) detected blue whale vocalizations in more northern waters offshore Nova Scotia, Canada during all months of the year, whereas in previous monitoring years the species was acoustically absent through April and May (Davis et al., 2020). In the present WIL data set, blue whales were acoustically detected in 5 months in 2018 (August to December) but only in three months in 2019 and 2020 (September to November). While variation in methodologies must be considered across studies, the combined evidence from Davis et al. (2020) (data from 2004 to 2014), Delarue et al. (2022) (data from 2015 to 2017), and the present study (data from 2017 to



2020) suggests that blue whales are shifting their distribution northward and are subsequently spending less time in the southern part of their range. Davis et al. (2020) proposed that the shift reflects animals following their prey species, whose distributions have been impacted by climate change.

During the present analysis, blue whale vocalizations were occasionally detected much farther south than reported by Davis et al. (2020), occurring in waters near SAV and BLE. These recorders were located farther offshore than those of the previous program (Davis et al., 2020), which may account for the varying findings. Indeed, such an offshore occurrence was proposed by Davis et al. (2020).

The lack of blue whale vocalizations detected at HAT is surprising given the annual occurrence described just south of the recording area (Davis et al., 2020). It may be that blue whale signals were so sparse that they were missed during analysis, that their vocalizations were masked by high sound levels from shipping, or that blue whales were not present off Hatteras. The latter would be of interest given that Davis et al. (2020) noted some areas of reduced detections of this species along the western Atlantic since 2010.

Song notes were the only blue whale acoustic signal confirmed in the data. Songs are believed to be produced by males (McDonald et al., 2001) and are most commonly heard from mid-summer to spring (Delarue et al., 2022; Širović et al., 2004). Therefore, these results should be considered a minimum as they are male-biased and the seasonality in vocal behavior can impact apparent occurrence trends. An absence of acoustic detections, particularly in spring and summer, may reflect animals being present but not vocalizing, or producing signals more difficult to detect. For example, a faint or distorted D call can be hard to differentiate from fin and sei whale vocalizations. Possible blue whale D call detections were detected off Hatteras and Virginia Inter-Canyon in the spring.

## 4.2 | Fin whales

Fin whale vocalizations were common in the data and were most prevalent at the northern stations, a finding in line with that of Davis et al. (2020). At VAC, fin whale vocalizations were detected in all recording months except June 2018 and May and June 2020. This occurrence was similarly described by Davis et al. (2020) where the species was present year-round but most acoustically common in winter (see region 8 in Davis et al., 2020). At HAT, fin whale vocalizations were detected from August to March, the same pattern observed in the 2004 to 2014 study (see region 9 in Davis et al., 2020). Fin whale acoustic occurrence at HAT showed some variability across years, with detections made from September to April in 2018–2019, but only from December to March in 2019–2020. As with blue whales, Davis et al. (2020) concluded that fin whale occurrence increased in northern waters after 2010. On the more northern Scotian Shelf, fin whale vocalizations were not detected for a portion of June from 2004 to 2014 (see region 3 in Davis et al., 2020), however, from 2015 to 2017 the species was acoustically present in all months of the year (see stn 24 and stn 25 in Delarue et al., 2022), lending further evidence to an increased northern occurrence through time. While no trend through time was noted at the Davis et al. (2020) Hatteras location, fin whale occurrence did decrease after 2010 off southern New England (see region 7 in Davis et al., 2020), and it is possible that the present data have captured this trend moving farther south. With only three years of data, it is unclear whether fin whales are spending less time at HAT through the years, ongoing monitoring is critical to observing this potential pattern.

From the more northern WIL station to the southernmost BLE station, months with fin whale occurrence generally decreased with decreasing latitude, with presence centered around November to February. These findings contrast with those of Davis et al. (2020), where fin whales were all but acoustically absent south of Wilmington. It seems that, in this southern region, fin whales occur farther offshore than the previous recorder locations of 2004–2014, a prediction astutely made by Davis et al. (2020).

The decrease in fin whale acoustic activity in spring and summer likely reflects a combination of animals moving from the area and a seasonal reduction in acoustic activity. All fin whale detections were of 20 Hz pulses, which form the song produced by males, predominantly from late summer to spring (Delarue et al., 2009; Watkins, 1981). Fin

whale 40 Hz calls can be difficult to differentiate from other baleen whale species, but possible detections were made in April, May, and June at VAC. These known seasonal fluctuations and bias to detection of males makes it difficult to say with certainty when fin whales were truly absent. Indeed, the species is known to occur in both high and low latitudes in all seasons (Edwards et al., 2015). An expansion of the monitoring area farther offshore could be revealing.

### 4.3 | Humpback whales

Similar to blue and fin whales, male humpback whales are prolific singers through the winter breeding season with songs in the North Atlantic heard from September through May, though some songs have been reported in summer (Kowarski, Cerchio, et al., 2021; Stanistreet et al., 2013). In addition to songs, humpback whale nonsong vocalizations, of which many types have been described (Rekdahl et al., 2015), can be heard throughout the year and are produced by both males and females. Given that this species is known to be so acoustically active, the chances of missing these whales on a monthly basis is low relative to other mysticete species. Therefore, the infrequent occurrence of humpback whales on the OCS south of Hatteras is likely reflective of the species' true occurrence. Davis et al. (2020) similarly found humpback whales to be acoustically rare on the continental shelf, providing evidence that humpback whales primarily utilize waters farther off the shelf break for migration between low-latitude breeding grounds in the Caribbean and high-latitude feeding grounds. Such offshore routes have previously been documented (Kennedy et al., 2013).

The northern HAT and VAC stations have likely captured whales moving through these areas during migration. The late winter to early spring detections may be animals moving north, while the fall to early winter detections may be animals moving south. Future directional analysis can attempt to confirm or refute these assumptions. Humpback whales off Cape Hatteras were less common in the present study than in the 2004–2014 analysis by Davis et al. (2020). The discrepancy in results could be caused by different recording locations or analysis methods. Alternatively, the species was using this region less in 2017–2020 compared to 2004–2014. Davis et al. (2020) found that humpback whales' acoustic occurrence on the more northern Scotian Shelf decreased after 2010, a trend potentially further captured by Delarue et al. (2022) on the Scotian Shelf where humpback whale vocalizations went undetected in March 2017, but were detected in all months from 2004 to 2014 (see region 3 in Davis et al., 2020). The shelf off Cape Hatteras should continue to be monitored to see if this shelf region is now also being less utilized by humpback whales.

### 4.4 | Minke whales

The occurrence of minke whales off the eastern US described by Risch et al. (2014a) was confirmed and expanded here, showing a pulse of occurrence through the OCS from November to April with fewest detections at the more northern VAC and HAT stations. Risch et al. (2014a) analyzed data from two areas in the vicinity of the present analysis, off Wilmington (station 6 in Risch et al., 2014a) and Jacksonville (stations 7 and 8 in Risch et al. 2014a). In 2009 to 2010, Risch et al. (2014a) detected minke whale pulse trains near our WIL station, in Onslow Bay, from November to March in 2009–2019, a pattern reflected at WIL in 2017–2020. From 2009 to 2011, minke whale pulse trains were detected at JAX in the months of December and January (Risch et al., 2014a). In contrast, the present analysis expanded the occurrence of these signals through to March at JAX in 2018, 2019, and 2020. Continued monitoring is required to observe whether this increase in minke whale acoustic temporal occurrence off Jacksonville is a trend through time or whether it reflects interannual variability.

Our analysis expanded the spatial coverage of the OCS by Risch et al. (2014a) and supports their proposed north–south seasonal migration of minke whales, and that the OCS may be breeding grounds. Indeed, minke whales



were seasonally acoustically detected from the southernmost BLE to the more northern WIL station. The most months with detections occurred at SAV where minke whale pulse trains occurred in September to April and July. This high-use region may be particularly important to the species. Risch et al. (2014a) proposed that minke whales on the OCS may be following the Gulf Stream, which many of our recorders fall within. Ongoing monitoring of this region in conjunction with changes to the Gulf Stream (e.g., due to climactic shifts) is critical to understanding distribution trends for this species over time. A more detailed look at minke whale occurrence and relative abundance based on the ADEON data is described in Kiehadrouinezhad et al. (2021).

As with fin, blue, and humpback whale songs, minke whale pulse trains are thought to be produced by males and be more prolific during the winter breeding season (Risch et al., 2014a). Indeed, these signals are all but absent from Canadian waters where the species is known to occur. For example, female minke whales occur in the Gulf of St. Lawrence in summer (Naud et al., 2003), but few pulse trains are recorded (Risch et al., 2014a). While minke whale seasonal occurrence on the OCS may extend beyond what is reported here, the overall trends are likely representative given that they are known to migrate to more northern waters in summer and during winter they seem more acoustically active, allowing for reliable detection using PAM (Risch et al., 2014a; Vikingsson & Heide-Jørgensen, 2015).

#### 4.5 | North Atlantic right whales

North Atlantic right whales were only detected in January at HAT, though possible upcalls were also detected at WIL and JAX. Our conservative definition for right whale occurrence, requiring upcalls to be clear and not associated with humpback whales, means that a number of the possible upcall detections were likely North Atlantic right whales. Instances where whales were not producing upcalls (e.g., producing gunshots only) would be missed using the present automated detector driven protocol. Furthermore, right whales are not as acoustically prolific compared to most of their baleen whale counterparts, making them less likely to be detected using PAM. Therefore, right whale acoustic occurrence results should be considered a minimum.

From 2004 to 2014, Davis et al. (2017) found that right whale vocalizations were largely absent from the southern US Atlantic coast from May to October, and when they did migrate to the region in the winter, they were found closer to shore than the present stations. Farther north in the Hatteras region, Davis et al. (2017) observed right whale acoustic occurrence decreasing over recording years, which may, in part, explain the minimal upcalls detected in 2017–2020 at HAT. In summary, while the North Atlantic right whale occurrence results presented here should be considered a minimum, these findings indicate that the species is not regularly acoustically present on the OCS.

#### 4.6 | Sei whales

The sparsity of sei whale detections at the northernmost stations (VAC and HAT) is somewhat surprising given findings by Davis et al. (2020) that the species was present in all seasons of the year at nearby sites. It is unclear whether sei whales were truly less acoustically common in 2017–2020 compared to 2004–2014. The present stations are not in the same locations as previous PAM programs, which may contribute to the varying results. Alternatively, the present analysis protocol may have underestimated the occurrence of this species whose vocalizations, like right whales, are not prolific. The sei whale acoustic repertoire continues to be discovered and described (Tremblay et al., 2019) and it is yet unclear whether the signals of this species change seasonally as has been described for some other baleen whales. Further analysis of the ADEON data set as more information comes to light may reveal an expanded acoustic sei whale presence or insight into trends.

The more inshore southern US stations of Davis et al. (2020) lacked sei whales, leading the authors to conclude that the animals must be located farther offshore. We confirmed this distribution, with sei whale vocalizations

detected seasonally at our comparatively more offshore stations from BLE to WIL in 1–2 months per year (between November and February) at each station. The limited sei whale detections off the southern US in 2004–2014 began as early as October, contrasting our detections, which were never earlier than November. More detailed data acoustic analysis of this acoustically cryptic species is required to confirm whether the species truly occurred on the OCS in fewer months in 2017–2020 compared to 2004–2014. Davis et al. (2020) did conclude that sei whale occurrence in northern latitudes increased after 2010. A subsequent decrease in time spent in southern regions would therefore be expected if this trend continued through to 2020.

#### 4.7 | NBHF clicks

NBHF clicks, which may include dwarf sperm whale, pygmy sperm whale, and/or harbor porpoise vocalizations, were not detected at the northernmost VAC and HAT stations but were detected through the remainder of the OCS. The most months with detections occurred at the deeper recording sites of WIL, SAV, and BLE. Based on current knowledge of the southern limits of harbour porpoise (Hayes et al., 2020), detections at BLE, SAV, and CHB were likely entirely dwarf or pygmy sperm whales whereas those at WIL were more likely to include harbor porpoise.

These findings expand, both spatially and temporally, the *Kogia* spp. distribution work of Hodge et al. (2018) and Cohen et al. (2022), where discrepancies in findings can be attributed to depth differences of recorders. Off Jacksonville, in 810 m water depth, Hodge et al. (2018) detected *Kogia* spp. clicks in 2014–2015 in all months of the year. Similarly, in the same area from 2016 to 2019, Cohen et al. (2022) acoustically detected *Kogia* spp. in all seasons of the year with recordings in 746–748 m water depth capturing less signals than those further offshore in 1,074 m of water (see stations Jacksonville and Blake Spur in Cohen et al., 2022). In contrast, in approximately 320 m water depth, NBHF clicks were almost entirely absent from JAX in 2017–2020. *Kogia* spp. vocalizations were common in 850–950 m of water off Cape Hatteras (Hodge et al., 2018) but were absent from the HAT station, which was in <300 m of water. The occurrence discrepancies across water depths likely reflect a combination of the species' preference for deeper waters and that the NBHF click detection range of shallow water recorders is expected to be shorter than deep water recorders. The present results expand what little is known of the range of these cryptic species and highlight the value of high sampling rate acoustic data that can capture the signals of these animals.

#### 4.8 | Sperm whales

Sperm whales were acoustically detected at all stations throughout the recording period. These findings are unsurprising given the cosmopolitan distribution of this species, whose regular acoustic occurrence in 2011–2015 recordings from the continental slope were similarly reported by Stanistreet et al. (2018) and in 2016–2019 by Cohen et al. (2022). Sperm whales have sexually segregated migrations, thus detections in more northern areas are likely to be males while those farther south may be a mix of females and males (Reeves & Whitehead, 1997). Stations with the most detection months were the northernmost VAC and southernmost BLE. Stanistreet et al. (2018) and Cohen et al. (2022) did not record in the Blake Escarpment area but had recordings from Norfolk Canyon, near VAC, and similarly detected sperm whale clicks throughout the year in 2013–2015 and 2016–2019. Overall, Stanistreet et al. (2018) detected whales in more months than the present study. This variation in results can largely be attributed to the recorders in 2011–2015 occurring in deeper waters (800–970 m water depth) compared to the present study where all stations except for SAV and BLE were in <500 m of water. Sperm whales, particularly when foraging, prefer deeper, more productive slope areas (Roberts et al., 2016) and the detection ranges at the deeper sites are expected to be greater.

## 4.9 | Beaked whales

Little is known of the ecology and distribution of many beaked whale species. Understanding these animals is of particular interest as they are deep divers that can be sensitive to the impacts of anthropogenic sound (Cox et al., 2006). Differentiating the signals of beaked whales from each other and those of delphinids can be challenging given the range of characteristics that can occur with off-axis clicks and the poorly described repertoires of these animals (Stanistreet et al., 2017). Therefore, for this species group, occurrence is likely underestimated and there may be some instances of misclassification across species. Here, we frame our results within the work done by Stanistreet et al. (2017) and Cohen et al. (2022), which described beaked whale acoustic occurrence in the western North Atlantic from 2011 to 2015 and 2016 to 2019, respectively. Previous acoustic recorders were located in water depths generally greater than 800 m (Cohen et al., 2022; Stanistreet et al., 2017), which contrasts to our comparatively shallower recorder locations. This difference between studies is expected to impact results as beaked whales are deep water species (MacLeod & D'Amico, 2006; Quick et al., 2020; Tyack et al., 2006). Unsurprisingly, in the 2017–2020 data set, beaked whale clicks were detected regularly at the two deepest stations (SAV and BLE) that ranged from 790 to 900 m water depth, once at the third deepest station (WIL) with a water depth of 456–464 m, and never at the stations ranging from 212 to 416 m water depth.

Blainville's beaked whale clicks were detected regularly at BLE (Figure 6), an area of the OCS not previously monitored via large scale PAM (Cohen et al., 2022; Stanistreet et al., 2017). Unlike in Stanistreet et al. (2017) and Cohen et al. (2022), Blainville's beaked whales were not observed at JAX, likely due to the present JAX station being in water too shallow (~300 m) for deep diving beaked whales, while previous Jacksonville recordings were in 746–800 m of water. Further offshore from Jacksonville in at Blake Spur in 1,047 m of water, Cohen et al. (2022) detected Blainville's beaked whale clicks in all seasons of the year. Stanistreet et al. (2017) and Cohen et al. (2022) also reported the species off Onslow Bay (called Gulf Stream station in Cohen et al., 2022), north of Wilmington where Blainville's beaked whales were detected in May 2020. In addition, Cohen et al. (2022) detected the species in the Bake Plateau, located north of Blake Spur.

Cuvier's beaked whale clicks were only identified in February, July, and May at BLE. This finding expands upon the work of Stanistreet et al. (2017) and Cohen et al. (2022) where the Blake Escarpment region was not investigated. Instead, previous studies identified Cuvier's beaked whale clicks on the shelf break in the regions of the WIL, HAT, and VAC landers; areas where the species was not detected during the present analysis. The difference in results likely reflects the present stations being shallow and, on the shelf, outside the habitat of Cuvier's beaked whales.

Gervais'/True's beaked whale clicks occurred regularly at SAV and once at WIL. Offshore from SAV and WIL, Cohen et al. (2022), detected clicks attributed to Gervais' beaked whales in all seasons of the year (see stations Gulf Stream and Blake Plateau in Cohen et al., 2022). Furthermore, offshore from WIL, Stanistreet et al. (2017) found Gervais' beaked whales to be most common. Indeed, all acoustic studies to date in the region provide evidence that this may be a high-use area for this species, even though sightings there have historically been lacking (Cohen et al., 2022). It is likely, based on conclusions from previous analysts which found True's beaked whales to occur in more northern areas (Cohen et al., 2022), that the clicks categorized as Gervais'/True's beaked whale in the present study, were produced by Gervais' beaked whales. Future detailed analysis of the present data set to investigate click characteristics, including IPIs, could be revealing.

## 4.10 | Delphinids

Small dolphins were common in the OCS of the eastern US, occurring in almost every recording month in every station. We were unable to tell from acoustic data, using the current protocol, which species were present or if multiple species occurred at any time. Bottlenose dolphins likely accounted for a portion of detections as vocalizations

thought to be produced by this species were identified in many of the recordings (see Figure 3; Simard et al., 2011). However, we could not rule out when Atlantic spotted, Fraser's, pantropical spotted, short-beaked common, or Risso's dolphins were present. Whistles from pilot/killer whales occurred without apparent seasonal trend across all stations (Figure 6). Many delphinid species are cosmopolitan and, therefore, their wide-ranging occurrence observed here year-round is unsurprising (Hayes et al., 2021; Mullin & Fulling, 2003). Future work is needed to identify consistent techniques to differentiate these species acoustically and then monitor for long-term distribution trends. With the support of historical visual sightings and machine learning techniques, Cohen et al. (2022) attempted to differentiate between delphinid clicks and proposed the detection of short-finned pilot whales, Risso's dolphins, and short-beaked common dolphins which were more common north of the present WIL station and may account for the present dolphin detections in those areas. With the exception of Cohen et al. (2022), previous large-scale PAM programs on the OCS have not reported on the acoustic occurrence of delphinids, likely due to the challenges described here in terms of species differentiation and the vast number of other species to report on. We propose that even if merged into a single species group, reporting on delphinid acoustic presence provides a more complete picture of the diversity of a region and can help to inform future, more species-targeted studies.

#### 4.11 | Summary and recommendations

This study continued the work of previous large-scale PAM programs, providing a glimpse into the marine mammal acoustic occurrence and diversity in more recent years and at additional sites. Our analysis protocol allowed us to determine monthly species occurrence in a large multiyear data set very efficiently, highlighting the value in applying techniques such as ADSV when analysis resources are limited (Kowarski, Delarue, et al., 2021). Visual sighting data collected during the ADEON program aligned with acoustic results for the more common species, but PAM was more effective at identifying more rare or visually cryptic species over a greater time period (Miksis-Olds et al., 2021).

In summary, cetaceans occurred year-round in the region with species acoustic diversity increasing in winter. While the scale of the ADEON program was significant, such 3-year programs are not sufficient for monitoring long-term trends of these long-lived species. By placing our findings within the context of previous work, we made several noteworthy observations. We found evidence that some baleen whales, particularly blue and sei whales, have continued a northerly shift first reported by Davis et al. (2020). Continued monitoring of such trends, which may be driven by prey movements associated with a changing climate, is critical for effective species management. The proposition by Davis et al. (2020) that blue, fin, and sei whales utilize the waters farther offshore the OCS than previous recording sites was confirmed, filling a notable knowledge gap. In the waters off Cape Hatteras, we found evidence that blue, humpback, right, and sei whales were less acoustically active in 2017–2020 than in 2004–2014. Future work off Hatteras should determine whether this was due to different recording sites or is a true indication of whales using the waters less. Beaked whale clicks were identified at SAV and BLE, two regions not included in previous, long-term, beaked-whale, PAM programs, providing a more complete picture of the distribution of these cryptic species. Further research off Savannah is needed to confirm what beaked whale species inhabit these waters (Gervais' versus True's beaked whales) and understand the significance of the area to these animals.

These notable findings should be appropriately considered by management bodies and by stakeholders that use the OCS waters. Successful management efforts are rarely achieved if we react only when species face extinction-level events. Instead, we must monitor subtle trends of the ecosystem and act accordingly when populations are still sufficiently viable. Future survey programs must engage in long-term, sustainable, year-round monitoring with consistent data ensured for years to come (e.g., Van Parijs et al., 2009, 2015, 2021). This study and its predecessors have proven the capability of PAM to be informative, and emerging work on density estimation from PAM (e.g., Kiehadroulinezhad et al., 2021) will prove extremely useful in assessing population trends.

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## AUTHOR CONTRIBUTIONS

**Bruce Martin:** Conceptualization; funding acquisition; methodology; project administration; supervision; writing – review and editing. **Emily Maxner:** Formal analysis; writing – review and editing. **Carmen Lawrence:** Data curation; formal analysis; writing – review and editing. **Julien Delarue:** Conceptualization; formal analysis; methodology; writing – review and editing. **Jennifer L. Miksis-Olds:** Conceptualization; data curation; funding acquisition; project administration; supervision; writing – review and editing.

## ORCID

Katie A. Kowarski  <https://orcid.org/0000-0002-1325-8321>

Jennifer L. Miksis-Olds  <https://orcid.org/0000-0003-1784-6849>

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## SUPPORTING INFORMATION

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