Passive Acoustic Monitoring for the North Carolina Renewable Ocean Energy Program

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Abstract

To characterize the presence of marine mammals in the Cape Hatteras region of the Gulf Stream, we deployed hydrophones in a mooring on the continental slope off Cape Hatteras, NC (35°6' N, 75°5' W) from January 2015 to November 2020 and developed a bioacoustic signal detection program to analyze the collected data. Analyzing a total of 20 months of data, we detected toothed whale (odontocete) sounds, including whistles and quacks, as well as baleen whale sounds, including those produced by fin whales and North Atlantic right whales (NARW). For comparison, we also analyzed data from one deployment of the Atlantic Deepwater Ecosystem Observatory Network (ADEON), approximately 13 km to the northeast of our site. For each type of marine mammal vocalization, we show the temporal pattern of the detections and compare our findings to other published studies documenting the presence and distribution of marine mammal vocalizations in this region.

Introduction

Physical processes along oceanic fronts, where different water masses meet, often create an environment favorable to marine life (Olson et al., 1994). The high primary producer (phytoplankton) biomass concentrated in fronts efficiently channels energy and nutrients through shorter food webs to higher trophic levels (Acha et al., 2015). Examples of highly concentrated biological assemblages associated with fronts abound. For example, sampling 154 locations across the Southern California Current, Powell and Ohman (2015) found high concentrations of zooplankton on the denser side of a frontal boundary. Enhanced productivity near fronts attracts top predators like marine mammals (Bost et al., 2009; Woodworth et al., 2012; Gilles et al., 2013).

Off Cape Hatteras, NC, at the Hatteras Front, cold Mid-Atlantic Bight (MAB) water converges with warmer South-Atlantic Bight (SAB) water (Savidge and Austin, 2007). Nearby, the western wall of the warmer, meandering Gulf Stream is another strong frontal boundary. Figure 1 provides a striking image of these fronts, with the strong gradient of sea surface temperature (SST) at the Hatteras Front extending northeast from Cape Hatteras. In this region, the "high density and diversity of marine mammals observed is likely associated with the hydrographic complexity," according to a cruise report from a Southeast Fisheries Science Center (SEFSC) survey in 2004 (NOAA NMFS Cruise Results: GU-06-03, 2006).

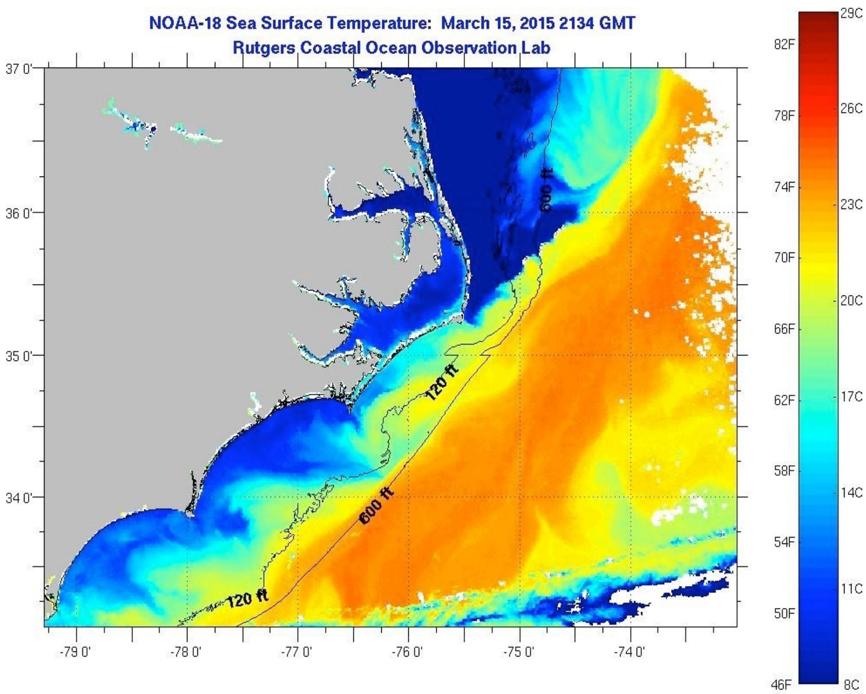

Figure 1: A snapshot of Sea Surface Temperature (SST) off the coast of North Carolina, illustrating the convergence of different water masses in the Hatteras Front and western Gulf Stream boundary. This image was taken on March 15, 2015 by Rutgers Coastal Ocean Observation Lab, using their Advanced Very High Resolution Radiometer (at https://marine.rutgers.edu/cool/sat_data/?product=sst&region=capehat&nothumbs=0).

Indeed, there is ample evidence that the Cape Hatteras region is a "hot spot" for many species of marine mammals (Table 1). At the ADEON site, Kowarski et al. (2022) detected migrating baleen whales, including fin whales, humpback whales, minke whales, and North Atlantic Right whales. They detected several species of odontocetes year-round, including sperm whales, dolphins, pilot, and/or killer whales. Over a period of almost three years (2013-2015), Stanistreet et al. (2018) found sperm whale activity year-round off Cape Hatteras, with peaks in the winter months. Baird et al. (2015) observed and tracked Cuvier's beaked whales, short-finned pilot whales, bottlenose dolphins, and short-beaked common dolphins off the coast of North Carolina, with many sightings on the shelf and slope off the tip of Cape Hatteras, NC. Analyzing 12 years of data of marine mammal strandings, Byrd et al. (2014) found a total of 34 different species of marine mammals stranding on the beaches of North Carolina. Thorne at al. (2017) concluded that "the Cape Hatteras region is an important hotspot of short-finned pilot whale density and foraging habitat."

Here, we contribute to the existing record of cetacean presence in the Cape Hatteras region (Table 1) with an analysis of hydrophone data acquired from 2015 to 2020.

Table 1. Scientific campaigns that include marine mammal monitoring near Cape Hatteras, NC

Program	***Dates***	***Description***
Navy Marine Species Monitoring program, Atlantic Fleet Training and Testing (AFTT)	2009 – present	The US Navy monitors marine mammals and sea turtles in order to reduce the impact of naval exercises upon these animals. This program is a collaboration with Duke University, Cascadia Research Collective, Southall Environmental Associates, Sea Mammal Research Unit of the University of St. Andrews, and others. One of the areas studied is the “Cape Hatteras Study Area”. Reports are posted at: https://www.navymarinespeciesmonitoring.us/reporting/atlantic/
NOAA NMFS AMAPPS		The Atlantic Marine Assessment Program for Protected Species monitors marine mammals, sea turtles, and sea birds along the entire east coast of the US. The AMAPPS website is: https://www.fisheries.noaa.gov/resource/publication-database/atlantic-marine-assessment-program-protected-species
ADEON	2017 – present	ADEON has deployed hydrophones at several locations in the Northwest Atlantic. One of their hydrophones is not far from NCROEP’s hydrophone. The ADEON website is: https://adeon.unh.edu/
National Park Service (NPS)	2015 - 2018	NPS publishes annual reports of marine mammal strandings on the Cape Hatteras National Seashore, available at: https://www.nps.gov/caha/learn/nature/annualreports.htm
Cape Hatteras: Where Currents Collide	2004 - 2005	NSF funded field program. See https://www.whoi.edu/science/PO/hatterasfronts/

Materials and Methods

Deployments

We analyzed the acoustic data collected from four deployments of hydrophones for two passive acoustic monitoring projects off the coast of North Carolina (Table 2): the North Carolina Renewable Ocean Energy Program (NCROEP) and the Atlantic Deepwater Ecosystem Observatory Network (ADEON). NCROEP deployed a mooring equipped with a hydrophone and a CTD on the continental slope off Cape Hatteras at 35°6’ N, 75°5’ W, at a depth of 230 meters. An Acoustic Doppler Current Profiler (ADCP) was also included in the mooring, but its data were analyzed and reported elsewhere (Muglia et al., 2020). The first NCROEP deployment lasted from late January of 2015 to late August of 2015. After the first mooring was retrieved, a second one was deployed to the same location. The hydrophone on the second deployment recorded sound from early September 2015 to late April 2016. A third deployment in 2020 successfully recorded data at this location from June to November.

Approximately 13 km to the northeast of the NCROEP mooring, at a depth of 294 meters, ADEON maintained a mooring deployed in November 2017 and equipped with hydrophones, a CTD, and other instruments.

Hydrophone data processing

Filtering and resampling

Prior to detecting odontecete vocalizations, we filtered the ADEON hydrophone data to have the same effective bandwidth as the NCROEP MAGI hydrophone, making it easier to compare these two deployments (Table 3). Prior to detecting the lower-frequency baleen whale vocalizations, hydrophone data from all deployments were filtered to have an effective bandwidth of 500 Hz and resampled at 1k samples/second. A variety of off-the-shelf and custom tools were then used to analyze the filtered and resampled data (Table 4).

Odontocete - Detecting whistles

For both NCROEP and ADEON hydrophone data, the Matlab-based tool Silbido (Roch et al., 2011) was used to automatically detect whistles in each of the recording intervals. Silbido was configured to look for whistles above 2 kHz. The SNR criterion was set to the default value of 10 dB. Before running Silbido on each recording interval, the recording was high-pass filtered with a cut-off frequency of 1 kHz. The “beta 2 (2015-03-11)” version of Silbido was used, from http://roch.sdsu.edu/Software.shtml. This version has a very low false alarm rate. Still, some post-processing was required in order to remove anthropogenic signals, including 12 kHz pings from side-scan sonar. This was accomplished programmatically.

Table 2. Hydrophone deployment and sampling information for the data analyzed in this study.

Deployment	***Dates***	***Location***	***Instrument***	***Sample rate (samples/s)***	***Duty Factor***	***Depth (m)***	***More information***
NCROEP (CF1E)	01/2015 - 08/2015	35° 08.335' N, 75° 06.362' W	Multi-Electronique Aural- M2 hydrophone; Seabird 37 SMP CTD	32,768	Recording 5 minutes out of every half hour	232	Dynamic range of 59 dB re 1mPa to 149 dB re 1mPa; no *in situ* calibration; raw data shared at https://www.ncei.noaa.gov/products/passive-acoustic-data
NCROEP (E663)	09/2015 - 04/2016	35° 08.335' N, 75° 06.362' W	Multi-Electronique Aural- M2 hydrophone; Seabird 37 SMP CTD	32,768	Recording 5 minutes out of every half hour	232	Dynamic range of 59 dB re 1mPa to 149 dB re 1mPa; no *in situ* calibration; raw data shared at https://www.ncei.noaa.gov/products/passive-acoustic-data
ADEON (EN615)	11/2017 - 06/2018	35°11.987’ N, 75°01.225’ W	JASCO Autonomous Multichannel Acoustic Recorder (AMAR)	375,000	On for 1 minute and off for 20 minutes	294	ADEON EN615 HAT dataset (adeon_en615_hat.amar509.9 data files) retrieved from https://www.ncei.noaa.gov/products/passive-acoustic-data; more information about ADEON hardware specifications can be found in Martin et al., 2018 and the ADEON project standards website (https://adeon.unh.edu/standards)
NCROEP (MAGI)	06/2020 - 11/2020	35° 07.879 N, 75° 06.585' W	Multi-Electronique Aural- M3 hydrophone; Seabird 37 SMP CTD	64,000	Recording 5 minutes out of every half hour	230	Dynamic range of 59 dB re 1mPa to 149 dB re 1mPa; no *in situ* calibration; raw data shared at https://www.ncei.noaa.gov/products/passive-acoustic-data

Table 3. The filtering and sample rates used per deployment prior to detecting whistles and quacks (high-frequency analysis).

Deployment	*Original sample rate (samples/sec)*	*Low-pass filtering (of original) prior to HF analysis (Hz)*	*Sample rate for HF analysis (samples/sec)*	*Effective bandwidth for HF analysis (Hz)*
NCROEP (CF1E)	32,768	--	32,768	16,384
NCROEP (E663)	32,768	--	32,768	16,384
ADEON (EN615)	375,000	32,000	93,750	32,000
NCROEP (MAGI)	64,000	--	64,000	32,000

Table 4. The detection tools used to analyze different detection types per deployment.

Detection type	*NCROEP CF1E*	*NCROEP E663*	*ADEON EN615*	*NCROEP MAGI*	*Tool(s) used*
Whistles	✓	✓	✓	✓	Silbido + Matlab to remove 12 kHz echosounder pings
Quacks	✓	✓			Pitch detector (swipep) + manual review
Fin whale 20 Hz	✓	✓	✓	✓	Custom Matlab + manual review
North Atlantic right whale calls	✓	✓	✓	✓	First pass with PAMGuard Whistle & Moan detector. Second pass with Ketos software, using a Deep Neural Network, followed by manual review

After detecting individual whistles, we calculated the total duration of the detected whistles for each recording interval. We divided this value by the duration of the recording interval to obtain a normalized metric per recording interval, the fraction of time spent whistling. We shall refer to this metric as the "vocalization metric" (VM) for whistles. VM values exceeding 1.0 were set to 1.0. (This may occur if there are overlapping whistles for the entire recording interval.)

We did not attempt to classify the whistles by species. Previous studies (Oswald et al., 2004) suggest that one needs an effective bandwidth of at least 24 kHz to classify dolphin whistles by species. The effective bandwidth for the first two NCROEP deployments is only 16 kHz.

Odontocete - Detecting quacks

Dolphins and pilot whales can produce a variety of "burst-pulse" vocalizations (Luis et al., 2016; Simard et al., 2011; Sayigh et al., 2013). These sounds are often categorized by the way they sound, including "quacks" and "barks". Since these sounds have pitch, like human vowels, we tried to detect "quack" sounds using a pitch detector, swipep (Camacho and Harris, 2008). This pitch detector has an implementation in Matlab at:

https://www.cise.ufl.edu/~acamacho/publications/swipep.m

Quack detection using swipep was performed on the first two NCROEP deployments (CF1E and E663), skipping any recording intervals with noise above a specified threshold. Recording intervals with one or more detections were reviewed manually to remove false alarms, using Raven Lite.

Mysticete - Detecting fin whale 20 Hz calls

Before detecting these baleen whale calls, we resampled the hydrophone data at 1k samples/sec. To detect fin whale 20 Hz pulses in the low-pass filtered data, a custom detector was implemented in Matlab, following the approach documented by Nieukirk et al. (2012). For each recording interval, we calculated the spectrum of the low-pass filtered recording interval. If the spectrum had a peak between 18 and 22 Hz, above a specified threshold, the recording interval was flagged for fin whale 20 Hz pulses. Each of the flagged intervals was manually reviewed (using Raven Lite) to determine the presence of 20 Hz fin whale pulses, thus removing any false alarms.

Mysticete - Detecting North Atlantic right whale calls

Kirsebom et al. (2020) developed python code (called Ketos) to detect North Atlantic Right Whales (NARW) using a Deep Neural Network (DNN). For details, see Kirsebom et al. (2020). The authors made their code publicly available at the following URL: https://zenodo.org/record/3736625#.YtSXl3bMKF4

In order to reuse the Ketos code, we resampled the hydrophone data at 1k samples/sec. With more than 30,000 wav files to process, the Ketos classifier would take too long. Therefore, we pre-processed the low-pass filtered hydrophone data by running PAMGuard's Whistle & Moan detector, looking for wav files that had one or more detections with a) SNR greater than 10 dB and b) in the frequency range of 90 Hz to 200 Hz and c) having a duration greater than 0.5 seconds. We then ran the Ketos classifier on this pre-processed dataset, generating a set of NARW detections per dataset.

Finally, wav files with Ketos detections were reviewed manually (using Raven Lite) to remove false alarms. As in Kowarski et al. (2022), if a NARW upcall was detected, we looked 2 hours forwards and backwards through the data for the presence of humpback whales. If there were humpback whales in this time window, the detection was not classified as NARW.

Indeed, some of the false alarms were due to minke whale calls or humpback whale songs. Since the detector was not designed for these species, we did not document the temporal pattern for these "accidental" detections of minke whales and humpback whales.

Data analysis

For whistles, we calculated the fraction of recording intervals (per month) having more than a specified threshold of 3 seconds of whistling per minute. For quacks and fin whale calls, we calculated the fraction of recording intervals (per month) having one or more detections. We then analyzed the temporal pattern of whistles, quacks, and 20 Hz fin whale calls per deployment.

Results and Discussion

Odontocete detections

A number of different odontocete bioacoustics signals were detected, including clicks, whistles, and quacks (Fig. 2). Whistle and quack bioacoustic signals were analyzed for this study; click signals were not.

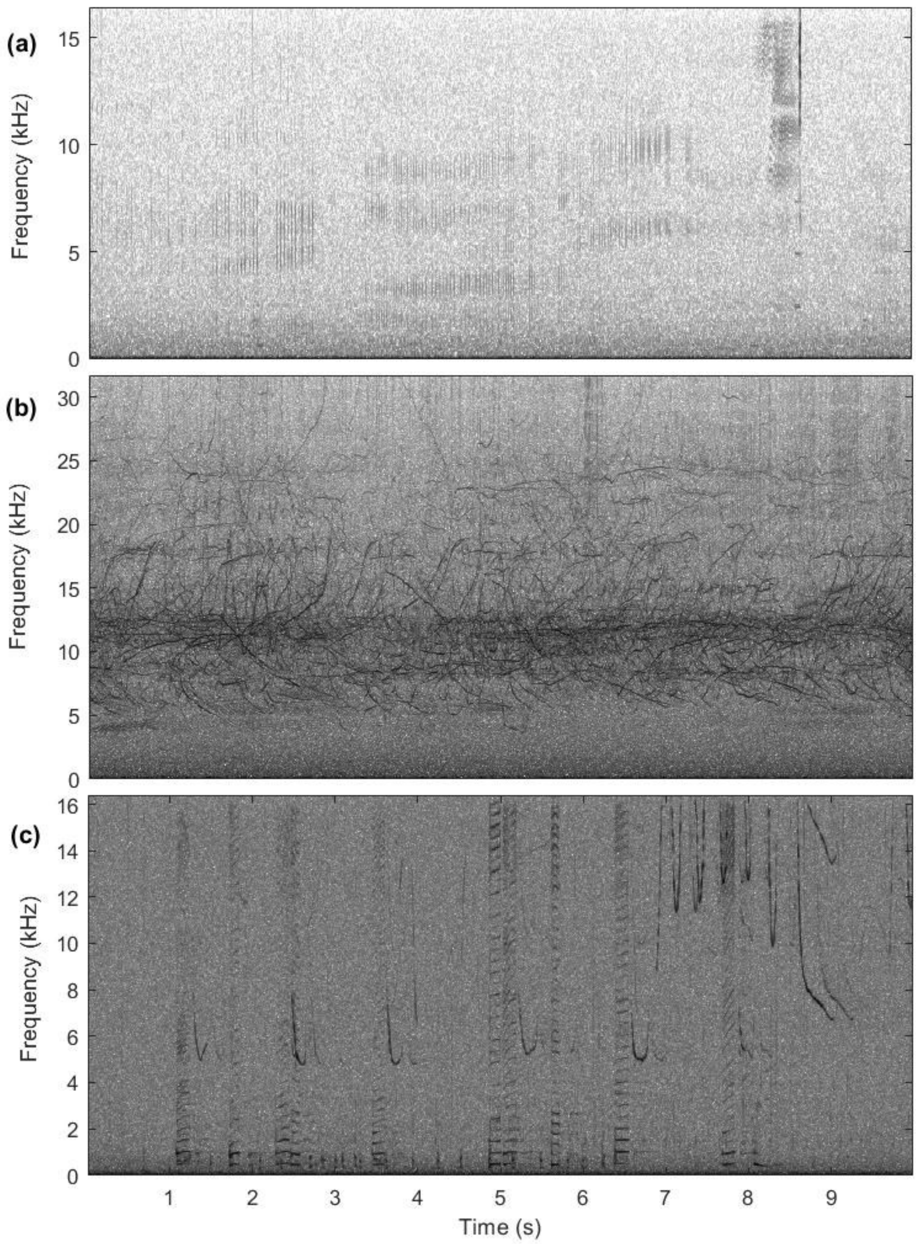

Figure 2: Spectrograms of high-frequency vocalizations (a) Click train from a CF1E recording interval starting at 16:00 (UTC) on January 22, 2015; (b) Constant, overlapping whistles from an ADEON EN615 recording interval starting at 19:30:56 (UTC) on 3/11/2018; (c) Dolphin quacks (and whistles) from a CF1E recording interval starting at 09:30 (UTC) on June 14, 2015.

Whistles

Whistles were detected in all deployments and during all months of the year (Fig. 3), although the later deployments (ADEON EN615 and NCROEP MAGI) had several times the amount of whistling compared to the first two NCROEP deployments (NCROEP CF1E and E663). The most whistles were detected by the ADEON EN615 deployment.

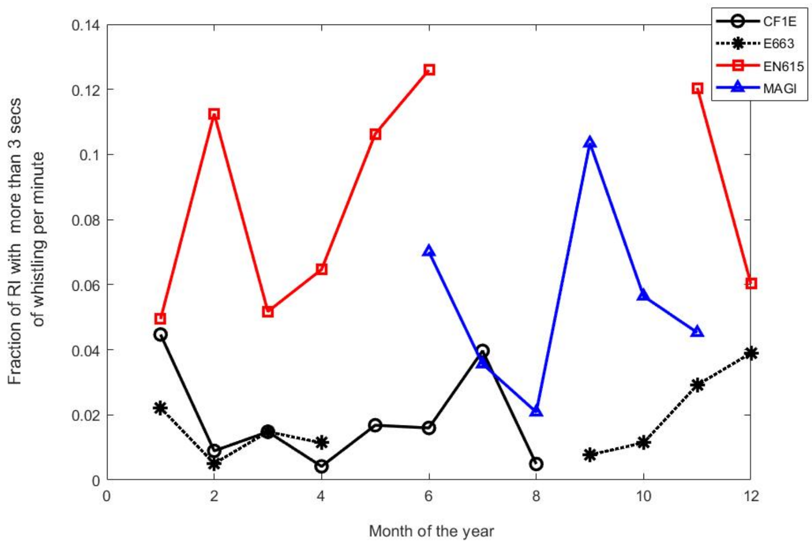

Figure 3: For each month of the year, the fraction of recording intervals (RI) from four deployments of hydrophones off the coast of North Carolina (2015-2020) that recorded more than 3 seconds of whistling per minute of recording.

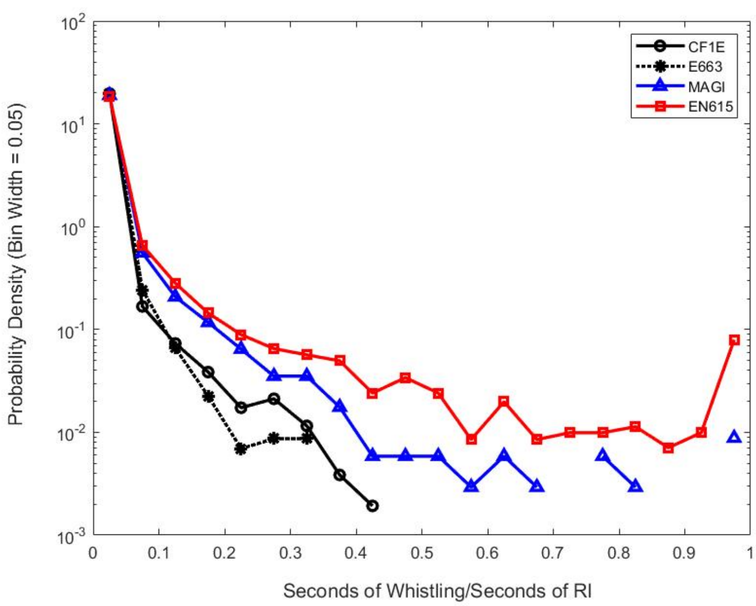

Figure 4: The probability density function (PDF) of the vocalization metric, the fraction of time spent whistling per recording interval (RI), for each of four deployments of hydrophones off the coast of North Carolina in 2015-2018 and 2020. The bin width is 0.05.

The vocalization metric for whistles is a random variable; therefore, it is useful to see how this random variable is distributed for each deployment, using the probability distribution function (PDF). The PDFs in Figure 4 show that there are some recording intervals in EN615 and MAGI where the vocalization metric is at or near 1, indicating that constant, overlapping whistles were detected throughout the recording interval. The spectrogram in Figure 2(b) shows an example of this. For the NCROEP MAGI deployment, this occurred on only three recording intervals. For ADEON's EN615 deployment, 55 recording intervals had constant, overlapping whistles; the majority of these occurrences were in the six-week period from late January to early March.

A probability density function of the median frequency of the whistles for the CF1E, E663, and ADEON EN615 deployments suggests that the most likely value of the median frequency of whistles is around 10-11 kHz (Fig. 5). It is interesting that the PDF of the median frequency has a separate peak below 8 kHz for all of the NCROEP deployments but not for the ADEON deployment.

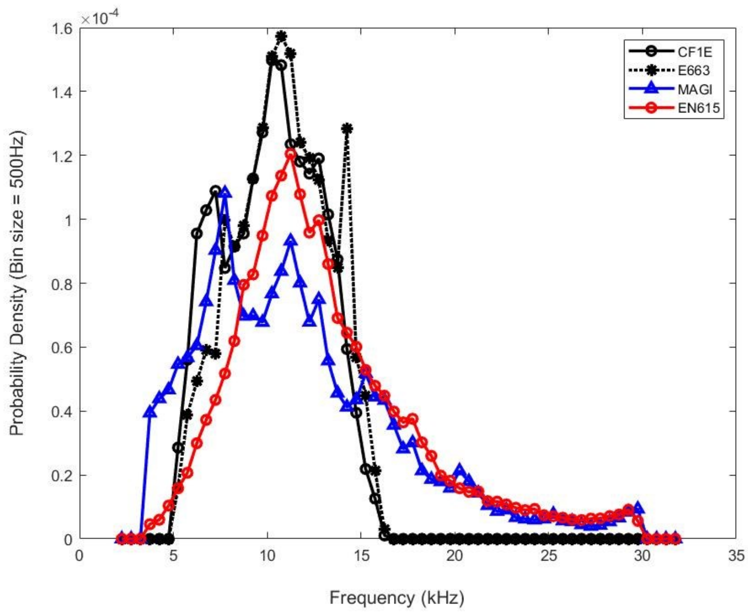

Figure 5: The probability density function (PDF) of median frequency of whistles for each of four deployments of hydrophones off the coast of North Carolina in 2015-2018 and 2020. The bin width is 500 Hz.

Note that the CF1E and E663 deployments are limited to a 16kHz bandwidth, which is half the bandwidth of MAGI and (our modified) ADEON EN615. Therefore, it is likely that the true distribution of the median frequency of whistles is closer to that found in the higher-bandwidth deployments.

Given the median frequencies of the whistles and our location, previous studies suggest that the species detected could include several species of dolphins as well as short-finned pilot whales (Baird et al., 2015; Thorne at al., 2017).

Quacks

For the first two NCROEP deployments (CF1E and E663), quacks were only detected in ten of the 16 months during which recordings were made (Fig. 6). They were not nearly as ubiquitous in the recordings as were whistles (Figs. 3 and 4). Figure 6 shows the fraction of recording intervals (per month) with one or more quacks. We found that the recording intervals with quacks are a subset of the recording intervals with whistles.

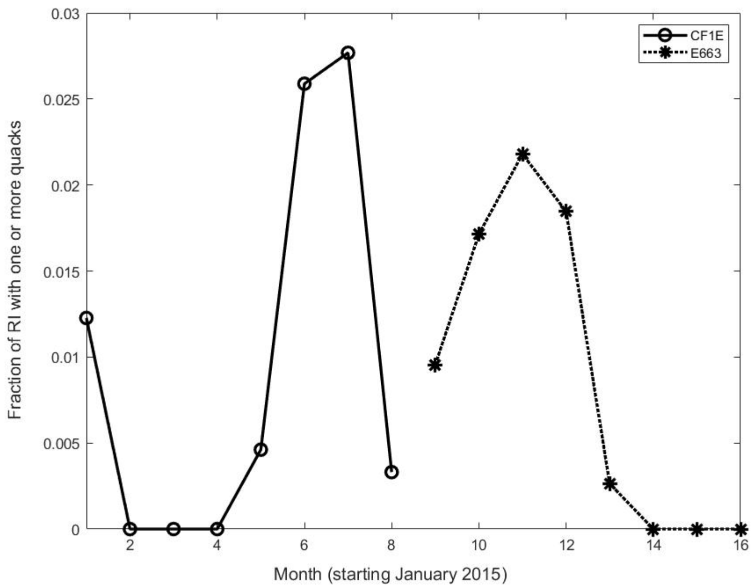

Figure 6: The fraction of recording intervals (RI) per month with one or more quacks for the first two NCROEP deployments (CF1E and E663) of hydrophones off the coast of North Carolina (2015-2016).

Mysticete detections

Several low-frequency vocalizations, generated by baleen whales, were also detected in hydrophone recordings from off the coast of North Carolina in 2015-2018 and 2020 (Fig. 7).

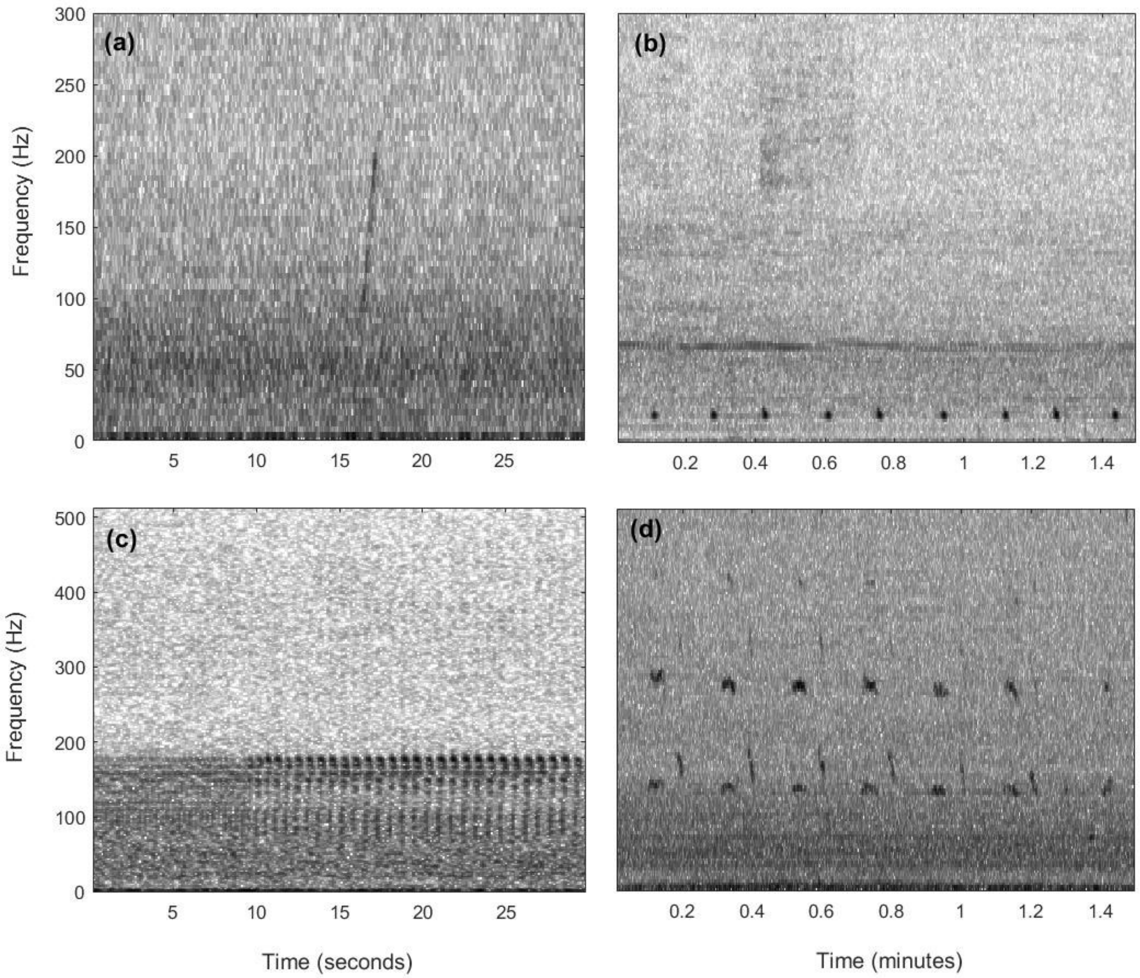

Figure 7: Spectrograms of low-frequency vocalizations (a) NARW upcall from an E663 recording interval starting at 08:30 (UTC) on February 12, 2016; (b) fin whale 20 Hz pulses from a MAGI recording interval starting at 00:30 (UTC) on October 21, 2020; (c) minke whale sound from a CF1E recording interval starting at 11:00 (UTC) on February 4, 2015; (d) humpback whale song from a CF1E recording interval starting at 00:00 (UTC) on April 6, 2015. Note that each row has the same scale on the y-axis; each column has the same scale on the x-axis.

Fin whale 20 Hz vocalizations were detected by more than one hydrophone deployment during January, February, March, October, and December and by at least one hydrophone deployment in April and September (Fig. 8), corresponding with migrations through North Carolina waters between high latitude feeding areas in the summer and tropical breeding and calving areas in the winter. Peaks in fin whale calls were observed in November (ADEON EN615), January (NCROEP E663), and February (NCROEP CF1E). The MAGI deployment recorded from late June to mid-November, likely missing the peak of the fin whale migration.

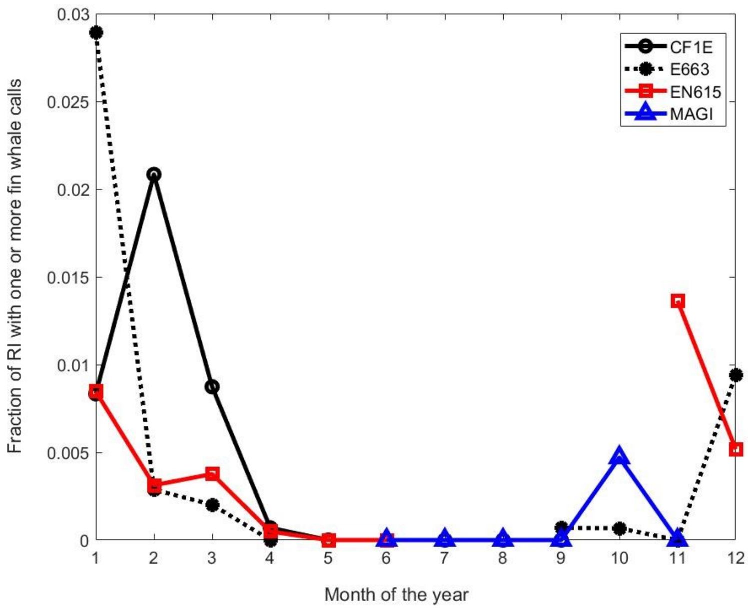

Figure 8: For each month of the year, the fraction of recording intervals (RI) with one or more fin whale 20 Hz calls from four deployments of hydrophones off the coast of North Carolina (2015-2018; 2020).

North Atlantic Right Whale (NARW) upcalls were detected in only two recording intervals captured by the NCROEP hydrophones, both from the E663 data set. The NARW upcalls were both detected on February 12, at 8:30 and 9:00 UTC. In the ADEON EN615 data set, we detected a NARW upcall in only one recording interval, the one starting at 05:39:56 on January 29, 2018. This is consistent with the findings reported in Kowarski et al. (2022). This consistency helps validate our approach.

As documented in Davis et al. (2020), many baleen whales pass through the waters around Cape Hatteras on their annual migrations. Davis et al. (2017, 2020) detected both fin whales and NARW in the Cape Hatteras region mostly in fall and winter. Our detections of fin whales fall within this window of time, with peaks in the number of detections in November (ADEON EN615), January (NCROEP E663), and February (NCROEP CF1E). We detected NARW in two hydrophone deployments analyzed here: in late January (ADEON EN615) and twice in a subsequent recording interval made in mid-February (NCROEP E663).

Conclusions

The literature provides ample evidence that the region of this study, off the coast of North Carolina near Cape Hatteras, is a "hot spot" for marine mammals. In general, the hydrophone data analysis presented here is consistent with these previous studies, since we detected a diversity of marine mammal bioacoustics characteristic of the region. Odontocete vocalizations, including whistles and quacks, and baleen vocalizations, including 20 Hz fin whale calls and NARW calls, were detected with our sampling and detection methods.

Additional detection tools that we may want to add to our hydrophone data analysis protocol in the future include one for detection of humpback whale vocalizations. We detected humpback whales indirectly when manually reviewing NARW detections, and Davis et al. (2017, 2020) noted detections primarily between October and January during the southward migration of these whales.

The physical oceanography in this region is complex, with variability due to the meandering Gulf Stream, the Hatteras Front, air-sea interactions, and other processes. As mentioned in the cited SEFSC Cruise report (NOAA NMFS Cruise Results: GU-06-03, 2006), this "hydrographic complexity" influences the biology, but it also influences the acoustics, varying the acoustic propagation near the hydrophone. If the acoustic propagation becomes more favorable, the effective area sampled by the hydrophone increases. So, for our recording intervals that were completely full of overlapping whistles, we are unable to determine if this is because there was a super-pod of dolphins nearby or if the acoustic propagation was more favorable. Perhaps both could be true. In the future, in order to accurately interpret the hydrophone data, we will need to simultaneously measure the sound speed profile in the region around the hydrophone.

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