ANALYSIS OF ACOUSTIC ECOLOGY OF NORTH ATLANTIC SHELF BREAK CETACEANS AND EFFECTS OF ANTHROPOGENIC NOISE IMPACTS

FY 2024 PROGRESS REPORT

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Introduction

Over 25 species of cetaceans utilize the shelf break regions of the US eastern seaboard, including several endangered species. Understanding patterns in species distribution, and the anthropogenic and environmental drivers that may impact their distribution, are critical for appropriate management of marine habitats. To better understand patterns in species distribution and vocal activity, NOAA's Northeast Fisheries Science Center (NEFSC) and Scripps Institution of Oceanography (SIO) collaboratively deployed long-term high-frequency acoustic recording packages (HARPs) at eight sites along the western North Atlantic shelf break. This work was conducted from 2015-2019, with financial support from the Bureau of Ocean Energy Management (BOEM). Likewise, the U.S. Navy has been monitoring the shelf break region at 3 to 4 sites since 2007. Together these combined efforts bring the total to 11 recording sites spanning the U.S. eastern seaboard, from New England to Florida.

Data from earlier HARP recorders have been analyzed in multiple previous studies (e.g. Davis et al. 2017; Stanistreet et al. 2017, 2018). This project focuses on analyses of the datasets collected from 2015-2019. The focus of our efforts in 2024 have been to finalize projects for submission to peer-reviewed journals and continue analyses of beaked whale and baleen whale species.

Objectives

The work this year was aimed at finalizing components for these key objectives:

1. Analyze beaked whale presence across HARP sites, with a focus on northern bottlenose whale and BWG presence.
2. Assessing effects of anthropogenic noise on beaked whale vocal activity
3. Analyze minke whale presence on the Navy HARP sites
4. Revising a manuscript comparing and contrasting two passive acoustic monitoring methodologies - towed array and shelf break HARPs - concerning beaked whale temporal, spatial presence and diving behavior.
5. Submit a manuscript that utilizes passive acoustic data from ten shelf-break environments to evaluate composition and dissimilarity of marine mammal community groups at different latitudes.

Acoustic Data Collection

Both the NEFSC and the U.S. Navy collected continuous passive acoustic recordings along the Atlantic continental shelf break of the United States at eleven sites beginning in 2015. The sites deployed in 2015 include Heezen Canyon, Oceanographer Canyon, and Nantucket Canyon (three northernmost sites) and U.S. Navy deployments at Norfolk Canyon (NFC), Hatteras (HAT), and Jacksonville (JAX). These were expanded in 2016 to include Wilmington Canyon & Babylon Canyon north of Cape Hatteras, and Gulf Stream, Blake Plateau and Blake Spur south of Cape Hatteras. (**Figure 1, Table 1**). HARPs were targeted to be deployed at depths of 700-1100 m, with the hydrophones suspended approximately 20 m above the seafloor. Each HARP was programmed to record continuously at a sampling rate of 200 kHz with 16-bit quantization, providing an effective recording bandwidth from 0.01-100 kHz. HARPs include a hydrophone comprised of two types of transducers: a low-frequency (< 2 kHz) stage utilizing Benthos AQ-1 transducers (frequency response -187 dB re: 1V/µPa, ± 1.5 dB, www.benthos.com), and a high-frequency stage (> 2 kHz) utilizing an ITC-1042 hydrophone (International Transducer Corporation, frequency response -200 dB re: 1V/µPa, ±2dB), connected to a custom built preamplifier board and band pass filter. Further details of HARP design are described in Wiggins & Hildebrand (2007).

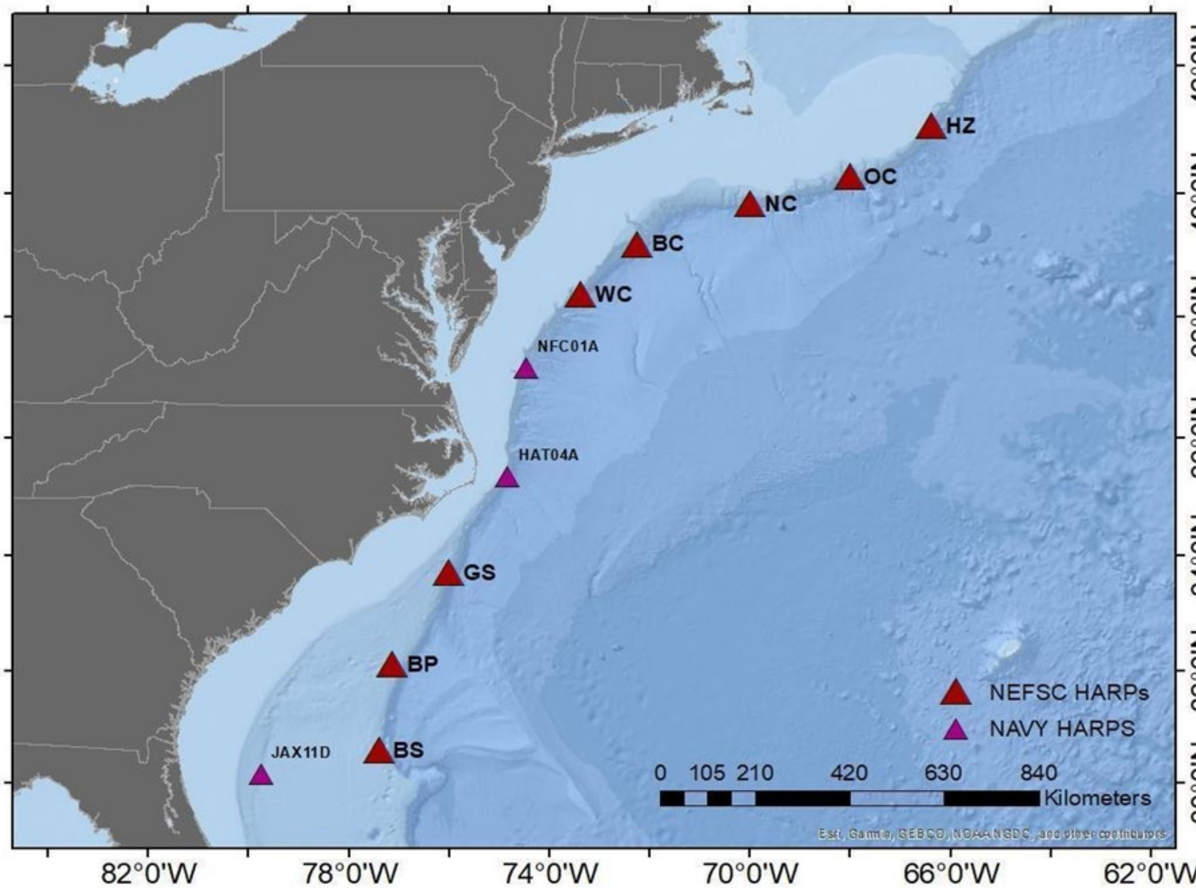

Figure 1. HARP deployment sites for data collected from 2015 through 2019.

Table 1. HARP deployment sites, recording dates and durations for 2015-2019. All HARPs recorded continuously at a sampling rate of 200 kHz. General latitude and longitude values are shown here, as each deployment had slightly different positions. The range of deployment depths are shown, as some deployments had different depths depending on where in the canyon the recorder landed.

Site Name; Location	Date Range	Latitude	Longitude	Depth (m)
WAT_HZ; Heezen Canyon	Jun 2015-May 2019	41.0619	-66.3515	845-1090
WAT_OC; Oceanographer Canyon	Apr 2015-May 2019	40.2633	-67.9862	450-1100
WAT_NC; Nantucket Canyon	Apr 2015-Jun 2019	39.8325	-69.9821	890-977
WAT_BC; Babylon Canyon	Apr 2016-May 2019	39.1911	-72.2287	997-1000
WAT_WC; Wilmington Canyon	Apr 2016-May 2019	38.3742	-73.3707	974-1000
NAVY_NFC; Norfolk Canyon	Apr 2016-May 2019	37.1665	-74.4666	950-1050
NAVY_HAT; Cape Hatteras	Apr 2015-Sept 2019	35.5841	-74.7499	980-1350
WAT_GS; Gulf Stream	Apr 2016-Jun 2019	33.6656	-76.0014	930-953
WAT_BP; Blake Plateau	Apr 2016-May 2019	32.1060	-77.0943	940-945
WAT_BS; Blake Spur	Apr 2016-Jun 2019	30.5838	-77.3907	1000-1005
NAVY_JAX; Jacksonville	Jul 2015-Jun 2019	30.1527	-79.7699	736-750

Analyses

I. Analyze beaked whale presence across HARP sites, with a focus on northern bottlenose whale and BWG presence.

Using the beaked whale neural net output developed in the earlier phase of this project (Solsona Berga et al. 2024), data from the HARP deployed at Blake Spur were analyzed from April 2016 - June 2019 for clicks matching the spectral properties of BWG. This click type has not been attributed to a species yet, but contains a frequency modulated upsweep that is diagnostic of echolocation clicks emitted by beaked whales (Baumann-Pickering et al. 2013). All click detection output from the neural net was reviewed in Matlab 2016b (MathWorks Inc., Natick, MA) using the detEdit software (Solsona Berga et al. 2020). detEdit groups nearby detections into "sessions", where the duration of the session is dependent on the number of clicks present and their temporal spread. Neural net classifications were changed to the correct species class if mis-labeled.

Out of 6255 sessions reviewed across 1143 days, four sessions contained clicks, which were spread across three days, that matched the characteristics of BWG (an example shown in **Figure 2**). These three days were all in 2017: January 7, May 22, and November 18. These data were then shared with master's student Kiersten Runte (Dalhousie University) for her thesis looking to examine and compare the characteristics of BWC, BWG, and BWST, as well as assess their global distribution. Preliminary results from that analysis were presented at the 2025 Society of Marine Mammology Conference in Perth, Australia.

In all previous beaked whale analyses using the WAT dataset, the presence/absence of the northern bottlenose whale (*Hyperoodon ampullatus*) was not reported as the detectors used were not designed to detect their clicks. However, in NOAA's stock assessment report for northern bottlenose whale, sightings are reported offshore of Georges Bank, though rare (Warring et al. 2015). Due to their endangered status in Canada's Species at Risk Act (COSEWIC 2002), and a protected species, understanding the southern limit of their range is important for their conservation. Colleagues at the Department of Fisheries and Oceans (DFO) Canada have a detector that is used for the detection and classification of northern bottlenose whale in passive acoustic bottom mounted recorder datasets (Stanistreet et al. 2022). The detector (BWD), is a modified version of the click detection process described in Baumann-Pickering et al. (2013), tailored more to the lower frequency range of northern bottlenose whale frequency-modulated clicks.

We analyzed the data collected at the Heezen Canyon site from April 2016 - May 2019 using the BWD detector. The resulting output was reviewed by a trained analyst for northern bottlenose clicks. Out of the three-year period, no northern bottlenose whales were definitively detected, and two encounters were labeled as "possible". These were also shared with our colleagues at DFO, who also agreed with our "possible" category based on the paucity of clicks received. As such, we did not review the data collected at the WAT sites further south and believe that their southern extent is north of Heezen Canyon, or in deeper water.

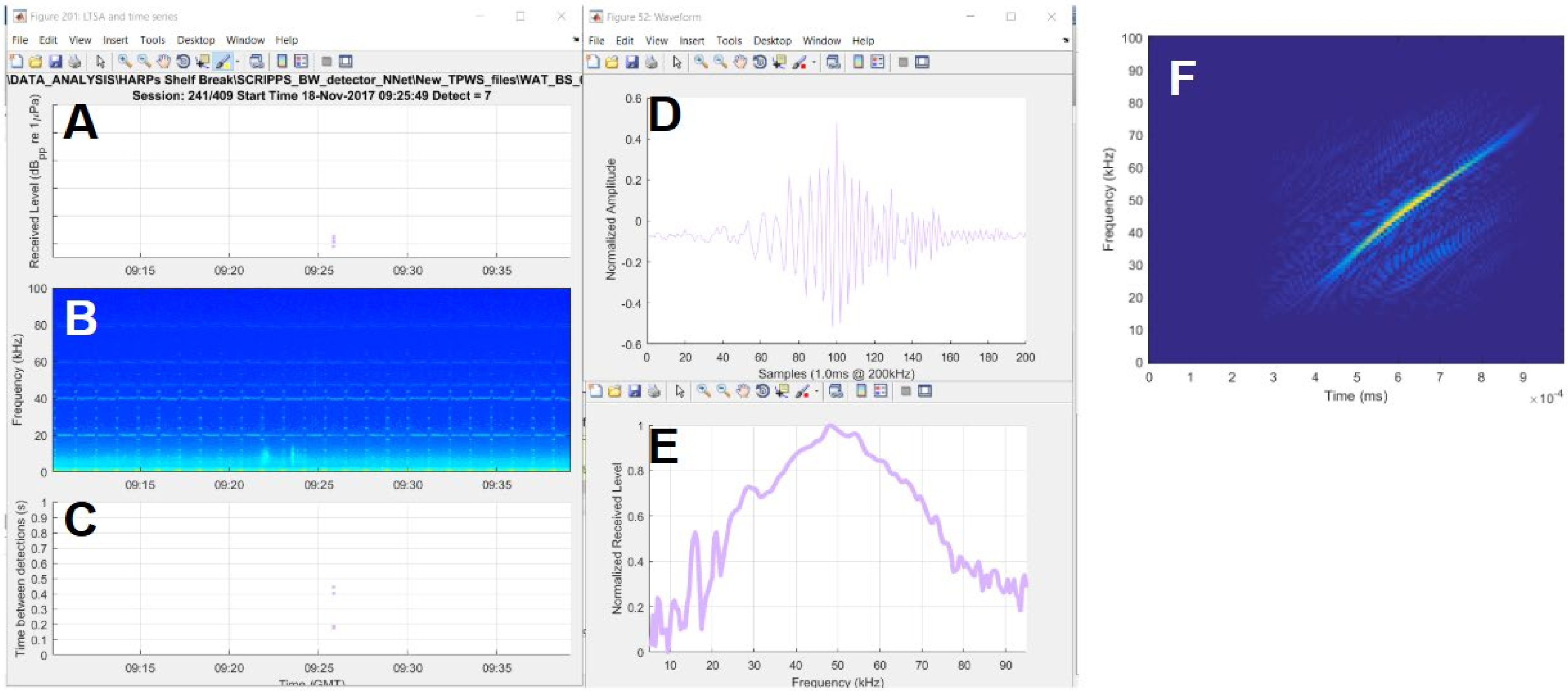

Figure 2. Example of BWG clicks found on the Blake Spur HARP. A) Time-received level plot of clicks identified by the neural net in one session that was confirmed by an analyst as BWG. B) Long Temporal Spectral Average (LTSA) of the time and frequency domain to provide context to the analyst while reviewing a session. C) Inter-click-interval plot showing clicks containing an ICI just <0.2 s and ~0.4 s, the latter of which indicates that some clicks in the click train were missed. D) Average waveform of one of the clicks in the session. Note the presence of many zero-crossings in the waveform, an indicator of BWG clicks. E) Average power spectral density (PSD) plot showing the distribution of energy within the BWG clicks. F) Wigner-Ville plot showing the diagnostic long upsweep present in BWG clicks.

II. Assessing effects of anthropogenic noise on beaked whale vocal activity.

For this component of the project, we have assessed the potential effects of mid-frequency active (MFA) sonar on beaked whale acoustic activity in the Western North Atlantic. The analyses incorporate data for several beaked whale species to detect acoustic behavioral responses to sonar operations in areas with varying levels of naval activity. Understanding the relationship between MFA sonar and the acoustic behavior of beaked whales is complex and requires the inclusion of natural temporal and spatial variability in click densities, e.g., caused by species or population-level seasonality, habitat preference, the behavioral context of echolocating, and individual variability. For this part of the project, analyses focused on the Navy HARP sites, as presence of MFA sonar is higher there than on the WAT sites.

A preliminary statistical analysis of sonar impact was conducted using a subset of the dataset (e.g. a few species at select sites), as not all classification labels of beaked whale species had been fully evaluated at that time (Van Parijs et al. 2021). The remaining data was subsequently processed for detection and classification of beaked whale signals in 1-min bins using a deep neural network (Solsona-Berga et al. 2024) developed and trained with funding from this project. The resulting labels from the neural network were validated using DetEdit (Solsona-Berga et al. 2020), and subsequent efforts for this reporting period were focused on conducting a comprehensive statistical analysis of the effects of MFA sonar on the acoustic behavior of beaked whales for three US Navy sites (NFC, HAT, and JAX). Automatic detection of MFA sonar was implemented using a modified version of the *Silbido* detection system (Roch et al., 2011) designed for characterizing toothed whale whistles. Method details were reported in Van Parijs et al. (2021).

Beaked whale detections with a peak-to-peak received sound pressure level (RL) above 118 dB_{pp} re 1µPa and sonar pings with an RL of at least 80 dB_{pp} re 1µPa were retained to maintain a consistent detection range. Acoustic detections were integrated by combining the data into 1-minute segments as detection units instead of individual detections of beaked whales and MFA sonar (**Table 2**). We studied five species of beaked whales—Sowerby's (Mb), Blainville's (Md), Gervais' (Me), True's (Mm), and goose-beaked whales (Zc)—across three Navy sites (**Table 2**). While four species (Mb, Md, Me, and Zc) were present at all sites, True's beaked whale was observed only at NFC and HAT. The highest overall presence of beaked whales occurred at HAT, which also had the lowest MFA sonar activity. In contrast, JAX, with the highest MFA sonar use, had the lowest presence of beaked whales. The shallower depth of JAX could also influence the reduced presence of these deep-diving species. Goose-beaked whales were the most frequently detected species, with particularly high numbers of 1-minute bins at HAT. Gervais' beaked whales followed similar patterns of occurrence as goose-beaked whales, though in lower numbers of 1-minute bins. In contrast, Sowerby's beaked whale had the highest 1-minute bin presence at the northern site, NFC.

Table 2. Summary of beaked whales and mid-frequency active sonar detections at three US Navy sites.

		NFC	HAT	JAX
		2014-2020	2015-2020	2016-2020
Beaked whales				
Effort 1-min bins (total in days)		1,702	1,812	1,130
Bins with presence	*Zc*	0.22%	12.77%	0.003%
	Me	0.13%	0.44%	0.004%
	Mb	0.12%	0.003%	0.0004%
	Md	0.0007%	0.005%	0.001%
	Mm	0.075%	0.02%	0%
Mid-frequency active sonar				
Effort 1-min bins (total in days)		1,333	1,793	1,128
Bins with presence		0.65%	0.21%	1.68%

For the statistical analysis, beaked whale presence was represented as a binary response variable defined as 1 (presence) if at least one echolocation click was detected within a minute and 0 (absence) for those during which no signal was detected. Five predictors (explanatory variables) were selected to evaluate the effects of MFA sonar exposure at different time scales. For short-term effects, we included presence/absence of MFA sonar per minute (*sPres*), with presence considered if at least one sonar ping was detected per minute, and three metrics of sonar exposure: the maximum peak-to-peak received levels (dB_{pp} re 1µPa) of all pings within a minute (*maxRLpp*), the cumulative sound exposure levels (dB_{pp} re $1\mu Pa^2 s$) of all pings within a minute (*cumSEL*), and the proportion of sonar within a minute (*sProp*) based on the total duration of the pings per minute. Presence/absence of sonar was included as an interaction term with the metrics of sonar exposure to accommodate the minutes without pings. For the possible long-term effect of sonar, we included the time-lapse since the cessation of sonar use (hereafter as sonar lag, *sLag*) as increasing number of minutes with sonar absence, and the consecutive time with sonar presence (*consPres*). To account for changes associated with natural variability, three predictors were selected based on temporal scale: *year* describing inter-annual variability, Julian day (*jd*) describing seasonality, and time of day (*timeofd*) for diel patterns. Time of day was normalized based on the time of sunrise and sunset at the location, defined as 0 the minutes at sunset and 1/-1 the minutes at sunrise.

The acoustic presence of beaked whales was modeled for each site and species individually using Generalized Estimating Equations (GEEs) in R software (version 3.6.2). Since beaked whale echolocation clicks are generally detected near the instruments for several minutes, GEEs allowed for estimates of population-average parameters representing averaged effects from the correlated data with asymptotically correct standard errors. The correlation was estimated using the *acf* function from the *stats* package (R Core Team 2022) and it ranged bfrom 15 to 60 minute segments across all sites and species. A block size (Zc: 60; Mb: 15; Me: 35; Md: 20; Mm: 20) was defined for each species as the cluster unit across all site's models to facilitate comparison between models, within which residuals were allowed to be correlated, while independence was assumed between separate clusters. Binomial GEEs were built with the package *geepack* (Halekoh et al. 2006, Yan and Fine 2004, Yan 2002) with a logit-link function, and Independence working correlation structure. Standard errors were extracted using the robust Sandwich variance estimator since it produces consistent errors even when the correlation structure is misspecified (Freedman 2006).

Potential issues of correlation and multicollinearity among explanatory variables were assessed in all models. Correlation between variables was identified with Pearson correlation plots and multicollinearity using a Generalized Variance Inflation Factor (GVIF) analysis with the function *vif* from the *car* package (Fox and Weisberg 2019). Starting with a full model with all variables fitted in a GLM, variables with high collinearity with a cut-off value of 3 (Zuur et al. 2009) were removed one by one using a stepwise procedure. After passing the GVIF analysis, each sonar-related variable was evaluated individually as a linear or smooth term for inclusion in models using the Quasi-likelihood under the Independence model Criterion (QIC) from the *geepack* package. All variables were found to be best fit with a smooth term and were built as cubic B-splines to allow for greater flexibility in the interaction with the response variable. The *bs* function from the *splines* package (R Core Team 2022) was used with the default settings to fit a third-degree polynomial with no inner knots. Year was treated as a factor variable in the model, and the periodic variables Julian day and time of day were treated as cyclic splines limited to four degrees of freedom using the *mspline* function in the *splines2* package (Wang and Yan 2024, Wang and Yan 2021) to help interpretability of the seasons and day light phases.

The importance of each explanatory variable was investigated by using a backward stepwise model selection procedure with the *drop1* function from the *geeasy* package (Petersen et al. 2022) to test the significance of each term, dropping non-significant (P>0.05) terms and re-evaluating the model until all terms were main effects or significant interactions. For all models, we first started with all non-sonar related variables and included *sLag* and *sPres*. For models where *sPres* was significant, an additional GEE model was developed including all sonar-related variables that quantified variability in the sonar exposure. For each variable in the final models, the average prediction of beaked whale presence was visualized with 95% confidence intervals generated using a parametric bootstrap with 1000 iterations.

Due to the limited acoustic presence of all beaked whale species at the JAX site (**Table 2**), we excluded this site from modeling efforts, as the data lacked sufficient power to assess behavioral responses to MFA exposure. Similarly, the sparse acoustic presence of True's and Blainville's beaked whale at the HAT and NFC sites, along with the lower presence of Sowerby's beaked whale at HAT, limited our ability to model these species (**Table 2**). As a result, we focused our modeling on the acoustic presence of Sowerby's, Gervais', and goose-beaked whales at NFC (**Figure 3**), while modeling Gervais' and goose-beaked whales at HAT (**Figure 4**). The best models revealed a dynamic pattern of whale presence that varied significantly across temporal scales (**Figure 3 & 4**). Year, describing inter-annual variability, and Julian day, describing seasonality, were retained by the models as important non-sonar variables for all three species modeled at NFC (**Figure 3**). Sowerby's beaked whale (Mb) presence decreased over the six-year period, whereas Gervais' (Me) and goose-beaked whales (Zc) had inter-annual cycles of presence that ranged from two to three years. Seasonality varied between the three species, but all exhibited a higher presence during the winter months. Normalized time of day, describing diel patterns, was retained by the model for *Mb* and *Me*, which both had a higher presence during the night. The probability of detecting beaked whales increased significantly at NFC during prolonged periods without MFA activity, particularly after 10-30 days of no sonar use. *sPres* was not retained as a relevant variable in the models for any of the three species at NFC, likely due to the minimal overlap between sonar pings and beaked whale presence within the 1-minute segments we analyzed.

At Hatteras (HAT), year and Julian day were important predictors for the presence of both Gervais' (Me) and goose-beaked whale (Zc) (**Figure 4**). Goose-beaked whale presence increased over the six-year period, while Gervais' beaked whale presence declined. Both species exhibited lower presence during spring and fall. However, goose-beaked whales had a peak in presence during the summer, while Gervais' beaked whales showed higher presence in the winter months, with a smaller peak in summer. Normalized time of day was retained as a significant predictor for goose-beaked whales, with presence highest around midday, though activity was detected throughout both day and night. The probability of detecting beaked whales significantly increased during extended periods without MFA activity (sonar lag), particularly after a month of no sonar use. Gervais' beaked whale presence was lowest immediately following sonar cessation, with minimal overlap in the 1-minute segments. Although goose-beaked whale presence was not near zero immediately following sonar cessation, it was significantly lower during periods of sonar presence.

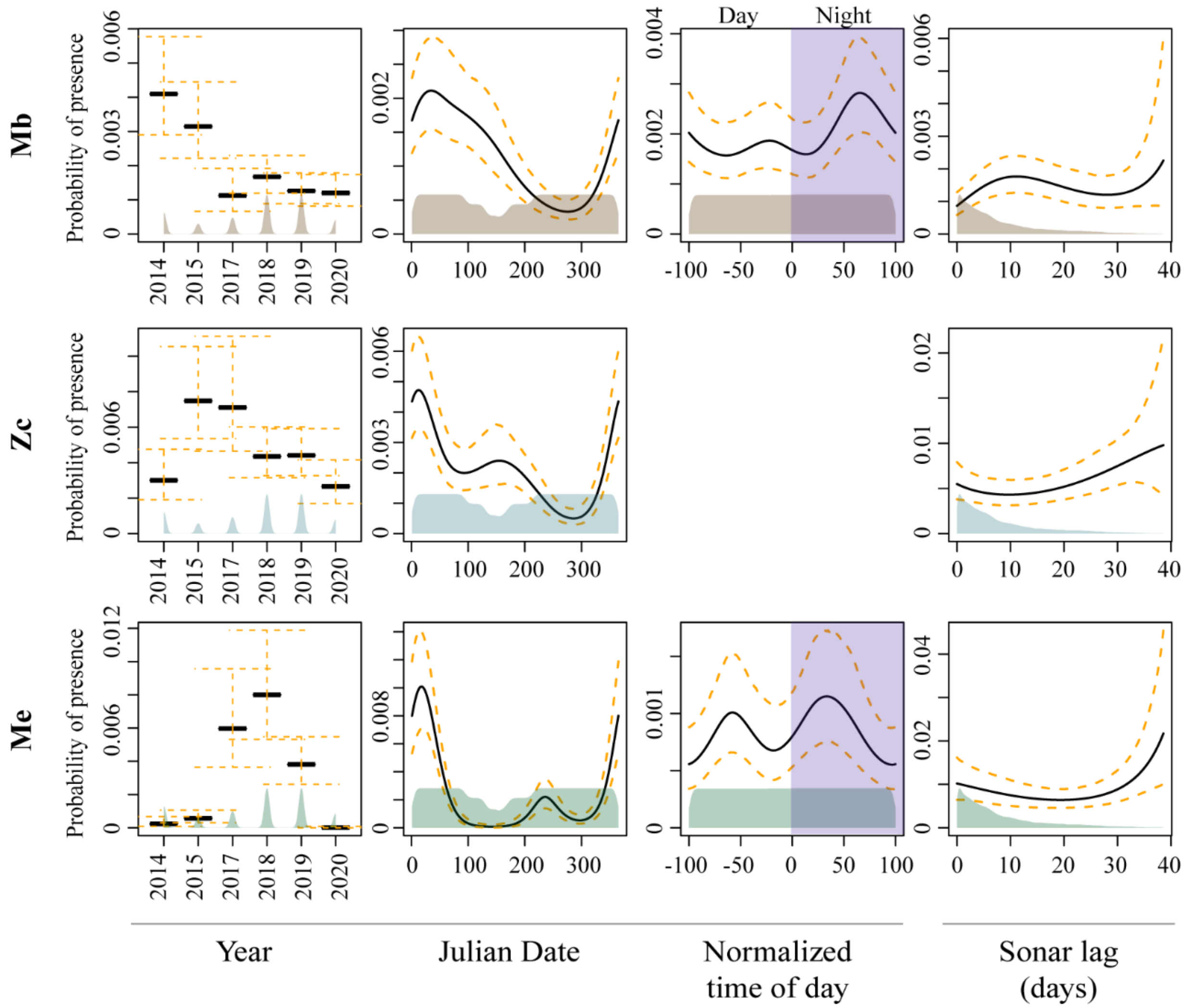

Figure 3. Generalized Estimating Equation (GEE) model results quantifying acoustical response of beaked whale species (Mb, Me, Zc) to MFA sonar at Norfolk Canyon (NFC). Model fit (black line) with confidence intervals (orange dashed line); bottom shaded area shows data distribution.

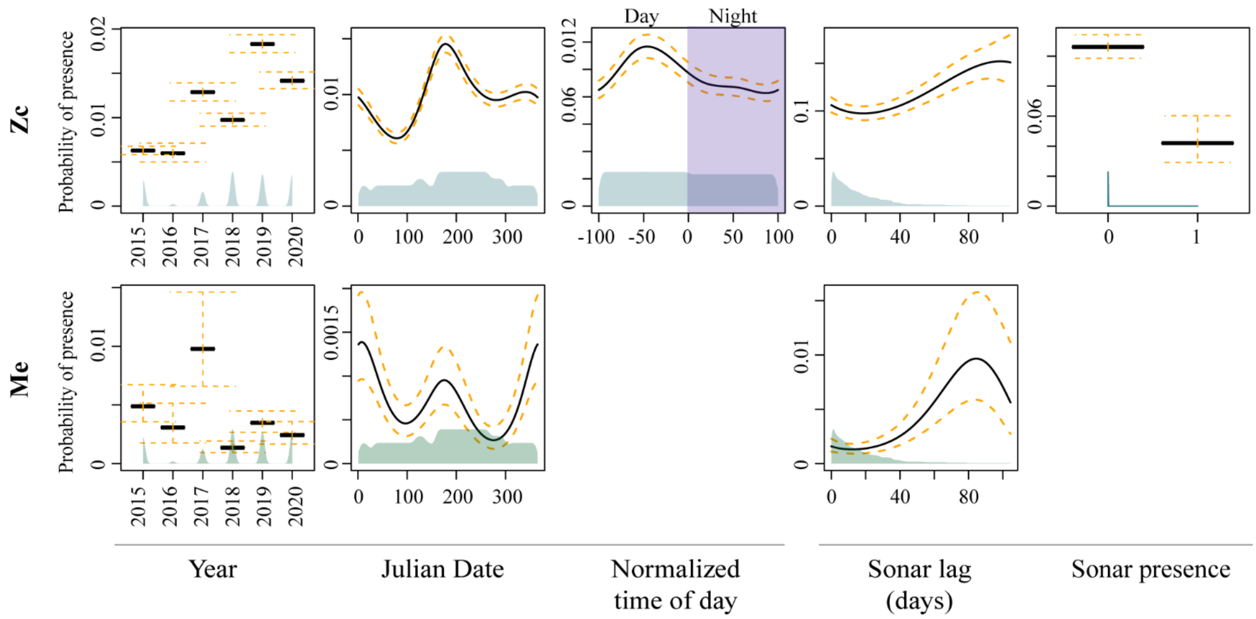

Figure 4. Generalized Estimating Equation (GEE) model results quantifying acoustical response of beaked whales species (Me, Zc) to MFA sonar at Hatteras (HAT). Model fit (black line) with confidence intervals (orange dashed line); bottom shaded area shows data distribution.

Goose-beaked whales, unlike the other beaked whale species in this study, frequently overlapped with sonar presence in the 1-minute segments at HAT, allowing us to assess how varying sonar exposure (e.g. at different time scales and intensity) influenced their behavior (**Figure 5**). Sonar-related variables, such as the cumulative sound exposure levels of sonar (cumSEL) and the proportion of ping duration per minute (sProp), were excluded from the model due to collinearity. The best model indicates that the probability of goose-beaked whale presence declines with increasing maximum levels of sonar use, reaching the lowest presence when exposed to pings received at above 120 dB_{pp} re 1µPa. Finally during this year's effort, we will write up this analysis for publication.

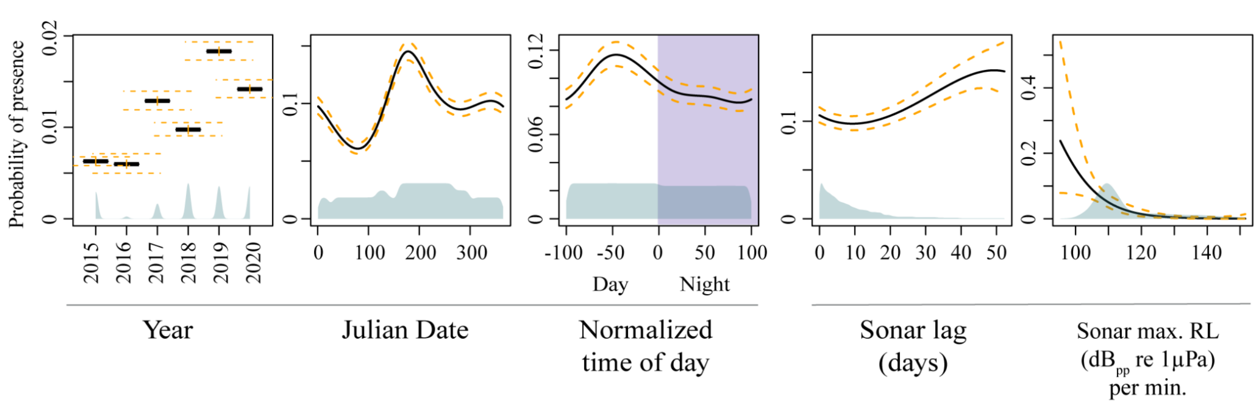

Figure 5. Generalized Estimating Equation (GEE) model results quantifying acoustical response of goose-beaked whale to different sonar exposure at Hatteras (HAT). Model fit (black line) with confidence intervals (orange dashed line); bottom shaded area shows data distribution.

III. <u>Analyze minke whale presence on the Navy HARP sites.</u>

We continued the daily presence analysis of minke whales at the Cape Hatteras HARP site using an improved minke whale detection algorithm written in python (https://github.com/xaviermouy/minke-whale-detector). This algorithm uses a binary ResNet18 deep neural network (DNN) to detect and automatically classify minke whale pulse trains based on spectrogram images. An analyst then manually reviewed the detections based on the algorithm's confidence using the spectrograms and audio files written in the detector output. Detections were organized by confidence score per day with the highest confidence detections reviewed first, until a true positive was identified.

Data were reviewed from 1 June 2018 – 29 October 2020, spanning a total of 853 days. Of that time, 2.3% (20 days) of days contained a positive minke whale pulse train detection. Minke whales were more commonly detected during the winter months of January to March across the two years, with more days of detection in 2019 (n= 15 days) than in 2020 (n= 5 days, **Figure 6**). These results will be incorporated into the HAT site comprehensive report currently in preparation.

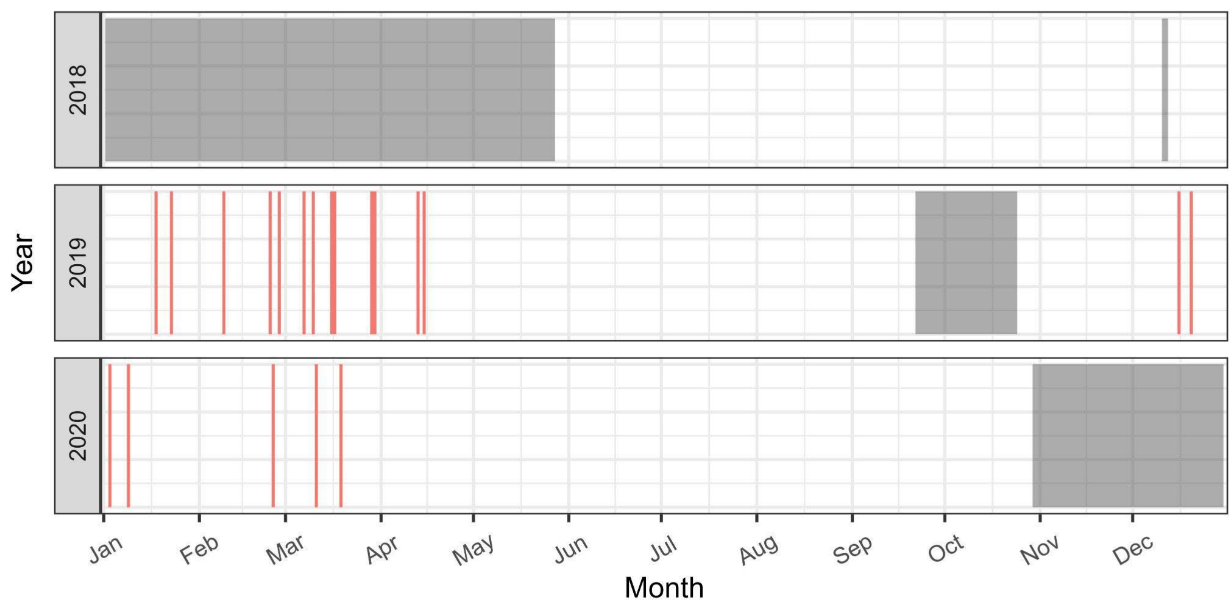

Figure 6. Daily acoustic presence of minke whales from 1 June 2018 – 29 October 2020 at the Hatteras HARP site. Red lines show days that minke whale calls were present. Grey shading indicates dates with no data.

Submitted analyses for publication

I. DeAngelis, A.I., Westell, A., Baumann-Pickering, S., Bell, J., Cholewiak, D., Corkeron, P.J., Soldevilla, M.S., Solsona-Berga, A., Trickey, J.S., Van Parijs, S.M.. “Habitat utilization of beaked whales in the western North Atlantic Ocean using passive acoustics.” Marine Ecology Progress Series, *in press.*

II. Haver, S., Corkeron, P., DeAngelis, A., Baumann-Pickering, S., Cholewiak, D., Davis, G., Frasier, K.,; Posdaljian, N., Rafter, M., Solsona Berga, A., Westell, A., Van Parijs, S., "Exploring the diversity of cetacean communities along the western North Atlantic Ocean shelf-break." Submitted to Royal Society Open Science, *in review.*

Conference presentations

Runte, K., Kowarski, K., Delarue, J., Martin, B., Hedgeland, D., Maxner, E.. “Longest Click in the Sea; Discovery of a novel beaked whale (Cetacea; Ziphiidae) click off West Africa” *presented at the 25th Biennial Conference on the Biology of Marine Mammals in Perth, Australia.*

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