Received: 17 June 2021 | Accepted: 16 June 2022

DOI: 10.1111/mms.12959

ARTICLE

Marine Mammal Science

Dive characteristics of Cross Seamount beaked whales from long-term passive acoustic monitoring at the Pacific Missile Range Facility, Kaua‘i

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Funding information
U.S. Navy, Grant/Award Number: N0007021WR0EP8F AA

Abstract

Beaked whale foraging pulses were detected on the Pacific Missile Range Facility (PMRF) off Kaua‘i, Hawai‘i, via long term passive acoustic monitoring. The unidentified pulses do not match foraging pulses of known species on the range but are similar to the unidentified beaked whale first detected at Cross Seamount, Hawai‘i. Although there has not been a visual confirmation of the unidentified beaked whale species, analysis of data collected from 2007 to 2019 has identified beaked whale foraging dive characteristics from echolocation pulses. From the 13 years of data, the most distinct patterns were that all foraging dives occurred at night and the nighttime foraging dive rate was 0.11 group vocal periods (GVP) per hour, with most detections on shallow hydrophones (625–1,000 m deep) over steep bathymetric slopes. Data collected during U.S. Navy training events were used to compare dive behavior during mid-frequency active sonar (MFAS) activity against baseline periods; it was determined that the whales reduced GVPs during sonar and these remained low for at least 3 days after the training events. These results are the first long-term record of acoustic signals from the Cross Seamount beaked whale and provide important insights into their habitat use and occurrence patterns.

KEYWORDS
beaked whales, dive behavior, foraging dives, Kaua'i, long-term data, passive acoustic monitoring, unknown beaked whale, U.S. Navy range

1 | INTRODUCTION

There are 24 known species of beaked whales globally, and many are difficult to study; due to their long duration deep foraging dives and cryptic surfacing behavior, they are infrequently visually sighted at the surface. Most beaked whale species have been acoustically identified by their echolocation pulses, which differ in duration, frequency content, and pulse interval length for each species (Baumann-Pickering et al., 2013, 2014). Similarly, many beaked whale species have been visually identified at sea based on their physical characteristics, including color patterns and teeth size and placement (e.g., Anderson et al., 2006; Pitman et al., 2006; Rosso et al., 2020). However, some species have only been identified from samples collected from strandings (Dalebout et al., 2002; MacLeod et al., 2005). Beaked whales have been found in diverse ocean environments from the deep open-ocean waters to shallow continental slopes and in climates from the Arctic to the warm tropics around the world.

Blainville's (*Mesoplodon densirostris*) and Cuvier's (*Ziphius cavirostris*) beaked whales have been observed and studied in the waters of the Hawaiian Islands through a combination of monitoring methods such as passive acoustic monitoring, satellite tags, and boat surveys, which have provided significant information about their diving behaviors. Satellite tagged Blainville's beaked whales off the coast of Hawai'i primarily use island slope waters (Abecassis et al., 2015). Visual surveys, photo-identification, and satellite tagging around the Hawaiian Islands have identified a Cuvier's beaked whale resident island-associated population (McSweeney et al., 2007) and both resident insular and pelagic populations of Blainville's beaked whales (Baird et al., 2011). In these studies, groups were small and averaged less than five individuals; Blainville's beaked whale groups have a mean size of three individuals, and Cuvier's beaked whale groups average two individuals (Baird, 2019; McSweeney et al., 2007).

A typical dive pattern for beaked whales is a single deep foraging dive, followed by a series of shorter, shallow dives and then a quick surface period before starting a new deep foraging dive (Baird, 2019; Schorr et al., 2014). During the deep foraging dive, beaked whales begin their search for prey by emitting a series of echolocation pulses that end in "buzzes" when a target is located. Cuvier's beaked whales are the deepest diving beaked whale and, on average, will forage at depths greater than 1,000 m for approximately an hour (Baird, 2019; Schorr et al., 2014; Shearer et al., 2019). Like Cuvier's beaked whales, Blainville's beaked whales are also extreme divers, but have mean shallower foraging dives of approximately 600–1,050 m depth and mean durations of 20–50 min (Aguilar de Soto et al., 2012; Baird, 2019; Johnson et al., 2004, 2006; Tyack et al., 2006). During foraging dives, Blainville's beaked whales were measured to have a narrow echolocation beam pattern but will scan their head and move their body to increase the ensonified area to find prey (Shaffer et al., 2013). From stomach examinations of Gervais' (*Mesoplodon europaeus*), Cuvier's, and Blainville's beaked whales from the Canary Islands and Cuvier's beaked whales from the North Pacific, these species forage mainly on cephalopods, but also prey on fish and crustaceans (Santos et al., 2007;

West et al., 2017). Similarly, MacLeod et al. (2003) found beaked whales around the world preyed mostly on cephalopods.

In the past, off-range U.S. Navy training events involving mid-frequency active sonar (MFAS) have been related to multiple global beaked whale stranding events (Cox et al., 2006; Evans & England, 2001; Tyack et al., 2011), which resulted in interest for more U.S. Navy funded research and monitoring of marine mammals, with a focus on beaked whales. Multiple studies have reported that compared to other cetacean species, beaked whales are more sensitive to MFAS, which can lead to behavioral responses that can sometimes be fatal (DeRuiter et al., 2013; Simonis et al., 2020). The beaked whales known to inhabit Navy ranges include: Blainville's, Cuvier's, and Longman's (*Indopacetus pacificus*) beaked whales at the Pacific Missile Range Facility (PMRF; Baird, 2019; Martin et al., 2020; Rankin et al., 2011); Baird's and Cuvier's beaked whales at the Southern California Offshore Anti-Submarine Range (SOAR; Falcone et al., 2017; Schorr et al., 2014); and Blainville's, Gervais', and Cuvier's beaked whales at the Atlantic Test and Evaluation Center (AUTEC; Gillespie et al., 2009; McCarthy et al., 2011; Tyack et al., 2011). Therefore, research on beaked whales located on Navy training ranges provides valuable information to the U.S. Navy and also provides more insight on sonar effects to beaked whale populations. These data also directly contribute to the development of Environmental Impact Statements (EIS), which authorize the Navy's need to maintain fleet resources, mission readiness, and meet defense objectives while also regulating activity and sonar usage in compliance under the Marine Mammal Protection Act (MMPA) and Endangered Species Act (ESA).

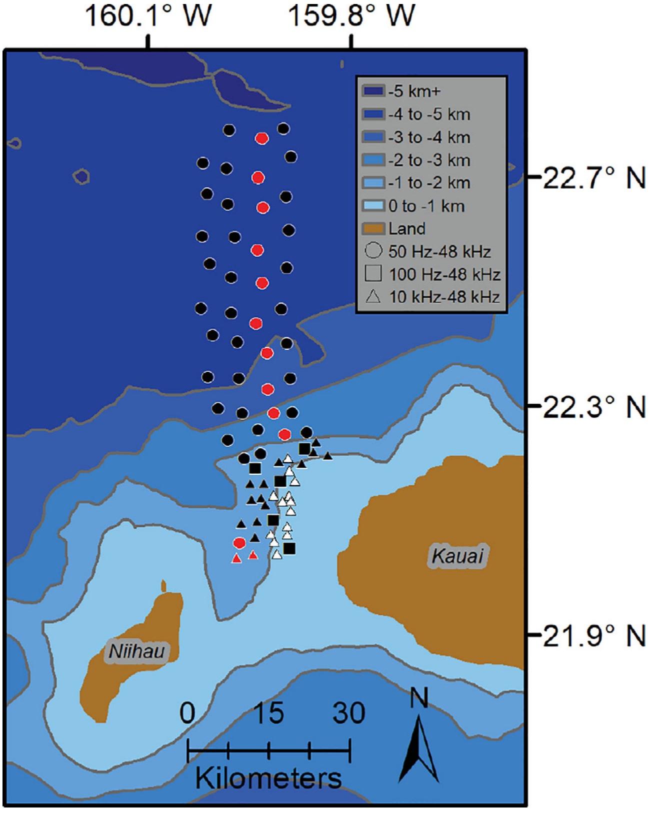

FIGURE 1 Map showing approximate locations of the hydrophones at PMRF with the bandwidth required to detect beaked whales. The original thirteen hydrophones from 2007 included the broadband hydrophones (100 Hz–48 kHz; squares) and a subset of high pass hydrophones (10 kHz–48 kHz; triangles) in the southern part of the range. Additional broadband hydrophones (black and red circles) were added in 2011. The red colored hydrophones became inactive in 2017 and were replaced with the white colored hydrophones in 2018.

As mentioned, Blainville's beaked whales, Cuvier's beaked whales, and Longman's beaked whales have been acoustically identified on bottom mounted hydrophones at PMRF located northwest of Kauaʻi, Hawaiʻi (Martin et al., 2020; Figure 1). Unidentified beaked whale pulses that were first acoustically detected at Cross Seamount, southwest of the main Hawaiian Islands (Johnston et al., 2008), have also been detected in long-term passive acoustic monitoring recordings from PMRF. The unidentified beaked whale pulse at Cross Seamount and PMRF has not been verified through visual sightings or linked to a known species and has only been identified from acoustically detected foraging dive pulses (McDonald et al., 2009). The detected pulses support the characteristics of known beaked whale species' acoustic signals, such as mid-frequency modulated upsweeps and rapid interpulse intervals (IPIs). For this study, the unknown detected foraging pulses were labeled BWC for the Cross Seamount beaked whales following Baumann-Pickering et al. (2013). Clusters of foraging pulses will be referenced as Group Vocal Periods (GVP) following McCarthy et al. (2011). By utilizing acoustic data collected over 13 years at PMRF, long-term forging dive characteristics of BWC beaked whales at PMRF can be analyzed to identify dive behavior unique to this species or in common with known beaked whale species. Because BWC beaked whales have been detected in Hawaiian waters where Blainville's, Cuvier's, and Longman's beaked whales are also foraging, it can be inferred that the species may share similar dive characteristics.

PMRF's underwater instrumented range includes a large-scale configuration of more than one hundred hydrophones. Its foremost purpose is to support U.S. Navy training and testing subsurface, surface, air, and space operations throughout the year. During periods of no Naval events on the range, or during specific training events, passive acoustic monitoring data of marine mammals are collected. Beaked whales have been detected over many years and during all seasons at PMRF.

With the large data set recorded at PMRF, intra-annual and multiyear BWC beaked whale foraging behavior was assessed, including foraging dive location preferences, GVP rates, and diel and seasonal patterns. A portion of this data set was collected during Submarine Command Course (SCC) events, which was compared against data collected during periods outside of U.S. Naval training and testing (considered the baseline period) to determine if Navy sonars had any effects on BWC beaked whale GVPs. There was no additional MFAS on the range during the recording periods used for baseline analyses; however, there may have been MFAS activity in between the baseline recordings, such that there could have been impacts to GVPs that were not accounted for in this analysis. These data provide valuable information about BWC beaked whales, whose habitat overlaps with a U.S. Navy training range with MFAS activity.

2 | METHODS

2.1 | Data collection

Data utilized for this study were recorded at PMRF using a subset of 13–62 PMRF hydrophones (depending on the year) from January 2007 through August 2019, typically comprising two continuous recordings a month, equaling about 96 hr per monthly recording. The starting date of this effort was chosen based on when broadband hydrophones were added to the range. Beginning in 2011, additional recordings were made before, during, and after SCC exercises that recur annually in February and August (Martin et al., 2015). SCC events were broken into two parts for analysis purposes; the first part, termed Phase A, consisted of training activity that did not include surface ship hull-mounted MFAS, while the second part, termed Phase B, consisted of training activity that included surface ship hull-mounted MFAS. Training activities and sonar usage during Phase B occurred equally during both the day and night. Starting in August 2012, a "Weekend" phase where there were no ship or sonar activity on the range occurred between Phase A and Phase B.

The PMRF hydrophones used in this study are seafloor mounted between 625 and 4,825 m depth and are sampled at 96 kHz using 16-bit analog-to-digital converters. Although the hydrophones' sampling frequency is below the

TABLE 1 Summary of the number of hydrophones utilized for each year of recording with the bandwidth capable of detecting beaked whale foraging pulses. The details of hydrophone recording configuration at PMRF are described in Martin et al. (2019).

Years	Hydrophones recorded
2007 to 2010	13
2011 to July 2012	31
August 2012 to July 2017	62
August 2017 to January 2018	52
February 2018 to August 2019	62

Nyquist frequency of the full extent of most beaked whale pulses and cuts off the upper frequency content, the hydrophones can record most of the lower frequency content, which can still be used for a detection. Hydrophone sensitivity increased in 2011 and the number of hydrophones recorded increased from 31 to 62 in 2012 (Table 1); the configuration of the hydrophones utilized on the Navy range and the hydrophone bandwidths are shown in Figure 1. Variation over the years in the number of hydrophones used to detect beaked whales were due to changes in available hydrophones with different recording bandwidths (e.g., from 2007 to 2010, most of the recorded hydrophones had a Nyquist frequency of 18 kHz).

2.2 | BWC pulse detections

The BWC pulse detector is an energy band detector based on the Blainville's beaked whale detector described in Manzano-Roth et al. (2016). The in-house developed C++ program (part of the Navy Acoustic Range WHale AnaLysis [NARWHAL] Algorithm Suite, described in Martin et al., 2020) applies a 16 k-point Fast Fourier Transform (FFT) then performs signal-to-noise ratio (SNR) tests for in-band energy (16–44 kHz) >1.5 dB and out-band energy (5–16 kHz) <1.15 dB. These criteria exclude pulses with low SNR, so not every pulse in a GVP is included and therefore estimates of dive duration are not included for analysis. Within the pulse detector, pulse duration was measured using an array of 2,048 64-pt FFTs with 98.4% overlap containing the pulse. The index of the FFT with the maximum magnitude summed from 15 kHz to 48 kHz was used to center the pulse within a 128-pt vector of magnitudes averaged from 19.5 kHz to 48 kHz. The SNR was calculated by dividing the 128-pt vector by the mean magnitude over the same bandwidth over the entire array of 2,048 64-pt FFTs. A 16-pt running average was applied to the 128-pt vector to create a 112-pt vector of smoothed SNRs, centered on the pulse. Starting at the center peak, the duration was calculated by incrementing either side until the smoothed SNR from 19.5 kHz to 48 kHz either reached a local minimum or dropped below 3.5 dB SNR.

Zimmer et al. (2008) found the maximum detection distance of Cuvier's beaked whale foraging pulses to be 4 km, but detection ranges can vary as the acoustic footprint of a dive can be dependent on group size. The probability of detection can also improve when the ambient noise is very low, such as when using sea-floor mounted hydrophones. At the AUTEC in the Bahamas, the maximum detection range of Blainville's beaked whale foraging pulses from the sea-floor hydrophones was found to be 6.5 km (Marques et al., 2009; Ward et al., 2008).

For BWC beaked whale detections at PMRF, detected pulses were automatically sorted into a GVP based on consecutive pulse detections on the same hydrophone or nearest hydrophones within 6 km distance, with a 1 min minimum dive duration and 10 min maximum between groups of pulse detection (e.g., detections were grouped if they occurred on the same hydrophones within 10 min of each other); if conditions were not met, a new GVP was formed. These GVP time limits were chosen given the possibility of a GVP occurring just off or at the edge of the range; due to the directional nature of beaked whale pulses these GVPs had a reduced chance of being detected. In

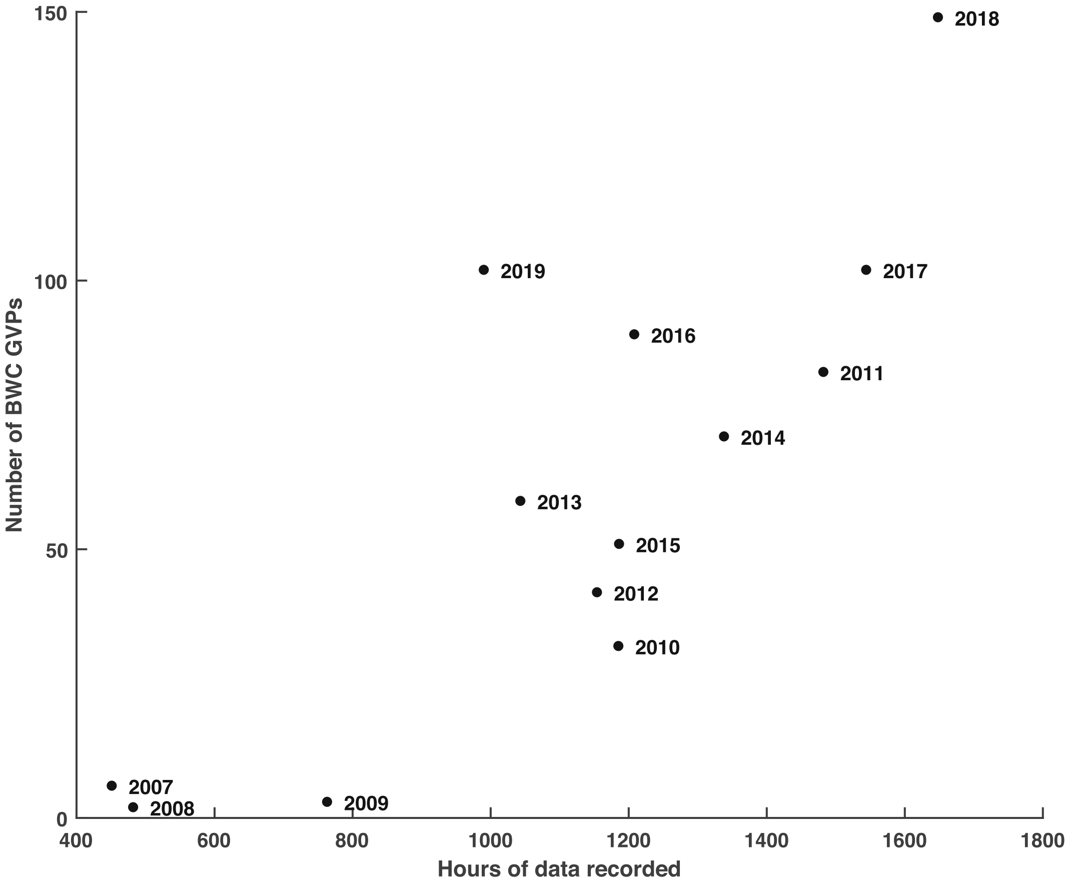

FIGURE 2 Recording effort of GVP detections, with each point representing a year from 2007 to 2019.

addition, only 13 hydrophones were recorded in the first 4 years of this analysis, so the opportunity to sample GVPs was lower and more GVPs would have been detected only on a single hydrophone. Therefore, in order to detect as many GVPs as possible, a short dive duration and a relatively long time window between pulses was allowed. GVP rates were calculated as the number of dives per hour of recorded effort; the number of hydrophones was not explicitly accounted for in this analysis although an effect can be observed (e.g., Figure 2). The exact location of the GVP is unknown since the pulses are not being localized, but it is assumed to be within 6 km of the hydrophone with the most detections, called the "prime" hydrophone.

GVP rates are independent of the number of hydrophones associated in a GVP, therefore one hydrophone with BWC foraging pulse detections was treated the same as a GVP detected over multiple hydrophones. However, when the hydrophone gain was increased in 2011 and the number of hydrophones recorded was expanded from 13 to 31 hydrophones to 62 hydrophones (in 2012) while still covering the same range area as the previous four years, the detections of foraging pulses also increased. When a GVP was detected over multiple hydrophones, the "prime" hydrophone was used to determine the bathymetric properties of where a GVP was detected. If a hydrophone detected BWC foraging pulses but was farther than 6 km away from the prime hydrophone, a new GVP is formed on another prime hydrophone and it was assumed that there were multiple GVPs occurring simultaneously. BWC foraging pulses on the prime hydrophone were used to estimate interpulse intervals (IPIs).

Cuvier's beaked whales hold the record for longest dive for marine mammals and have average foraging dive duration of approximately 60 min (Baird, 2019; Quick et al., 2020; Schorr et al., 2014); therefore, it was reasoned that BWC beaked whale GVP dive duration is not likely to extend longer than an hour. If a GVP was >1 hr, the phones on which the dive was recorded were manually inspected to determine whether the dive could be spatially separated into multiple BWC beaked whale GVPs. All foraging pulse spectrograms and time series were manually validated for IPI, time series length, and frequency content. IPIs were calculated by binning all IPIs between detected pulses in a GVP into a histogram, with the peak bin selected to represent the overall GVP IPI.

2.3 | Long-term data analysis

Bathymetry data (15 arc-sec resolution) for the hydrophone range was acquired from the General Bathymetric Chart of the Oceans (GEBCO; Weatherall et al., 2015) to characterize dive location preferences by water depth and seafloor slope around each hydrophone. While water depth at the hydrophone was provided by PMRF, the average water depth around each hydrophone was calculated by using depths within a 36 km^2 box centered at each hydrophone. Note that since the actual depth of the GVP were unknown, it is these water depths that were utilized in the habitat analyses. Slope gradient was calculated from the maximum and minimum depth divided by the distance between both points to represent the average slope surrounding the hydrophone. Oceanographic seasons for these analyses were defined as winter (February to April), spring (May to July), summer (August to October), and fall (November to January) (Flament et al., 1996). Diel periods were defined as daytime = 0700–1700, night = 1800–0600 (October to March), daytime = 0600–1800, night = 1900–0500 (April to September).

All analyses were calculated using the total number of recording hours and were independent of the number of hydrophones recorded during each year. Chi-square tests were used for an initial analysis of spatial and temporal variables. Chi-square goodness-of-fit tests were primarily used to determine if there were patterns in GVPs between seasons, months, time of day, and lunar cycle, and if differences existed between baseline periods and during U.S. Navy events on range. Expected results from the chi-square test were calculated based on the total hours of recording effort and assumed an equal chance of detection across all variables for a simplified scenario; these were compared against observed values.

In order to investigate comprehensive spatio-temporal patterns in BWC beaked whale distribution, generalized additive models (GAMs) of BWC beaked whale GVPs were developed using the mixed GAM computational vehicle (*mgcv*) package in R version 3.6.1 (R Core Team, 2019; Wood, 2006). GVPs were binned into 1 hr periods based on dive start times, and the presence or absence of dives in all 1 hr periods of recording effort across all available hydrophones was assessed as a function of spatial predictors (the slope and depth around each hydrophone), temporal predictors (year, month, season, start hour, and percentage of lunar illumination), and predictors related to the occurrence of the SCC training events. For the latter there were two covariates fit to the models. The first was "Period," which included 3 days Before or 3 days After the SCCs, the Weekend in the middle of the SCC ($M = 2.3$ days) between Phase A and B, During (including both phases), and None for all other times (i.e., baseline); The second was the "SCC Phase" consisting of Phase A ($M = 2.3$ days), and Phase B ($M = 2.9$ days), or None. To select which predictor variables should be included in the model, a likelihood-based smoothing selection method was used with the restricted maximum likelihood (REML) criterion.

Each predictor variable was included in the separate spatial and temporal models using a smoothing function defined by a cubic regression spline with shrinkage. The models also tested for interactions between the variables. Because the number of hydrophones that were recorded changed over the years, the number of hydrophones was used as an offset in the models. Multicollinearity was tested using the variance inflation factor (VIF) in the R package *car* (Fox & Weisberg, 2019), while model residuals were tested for autocorrelation using the autocorrelation and partial autocorrelation functions in R. If autocorrelation was found, it was corrected using an autoregressive-moving average correlation structure (corARMA) within the GAM. All environmental predictors were included in the initial models, and then any nonsignificant variables were excluded and the model was refit until the REML score and explained deviance were maximized and only significant variables were included. The SCC-related covariates were examined separately in standalone models.

3 | RESULTS

From January 2007 to August 2019 there were 14,478 total hours recorded (12,546 baseline hours, and 1,932 SCC hours) and 792 BWC beaked whale GVPs (717 during baseline period, 34 during Phase A and 41 during Phase B) detected. As would be expected, the number of detected GVPs increased as the number of recording hours increased over the years (Figure 2). The highest number of GVPs (149) occurred in 2018, which also had the most hours of recording effort (1,642 hours). In 2019, the only available data were from January to August 2019, and therefore the data do not represent a full year. In addition, no SCC data from 2019 were available for analysis, so the SCC data are only from 2011 through 2018.

The BWC echolocation pulses follow similar patterns of other beaked whales foraging pulses described by Baumann-Pickering et al. (2014), such as having a frequency modulated upsweep and short IPI. The BWC foraging pulse detected at PMRF has a distinctive frequency upsweep starting from approximately 18 kHz to greater than 48 kHz (the maximum frequency limit of the PMRF sensors; Figure 3) and a mean duration of 0.66 ms ($SD = 0.02$); however, the pulse's full length is clipped due to the aforementioned bandwidth limitations. The IPI median was 0.13 s and the mean was 0.14 s ($SD = 0.07$, based on an $n = 512$ GVPs). GVPs with IPI >2 s or GVPs with not enough data to estimate an IPI were excluded in the calculation of the median IPI; high IPIs are usually due to pulse detections on hydrophones on the edge of the range where consecutive pulses are more likely to be missed. Although the BWC pulses detected at PMRF are bandwidth limited, there is enough low frequency energy to detect and distinguish the foraging pulse from other known beaked whale species' foraging pulses found at PMRF. There is also enough energy to classify it as comparable to the pulses found at Cross Seamount (Figure 4), where the pulses had a frequency upsweep from 37.2 kHz to 100 kHz, a pulse duration of 0.93 ms, and IPIs of 0.11 s (McDonald et al., 2009).

GVP dive rates were initially calculated using all recording hours, which resulted in a mean dive rate of 0.05 GVPs/hr between 2007 and 2019. However, after inspection of the dive data, it was found that almost all dives occurred at night (1800–0600 HST), supporting the findings from Johnston et al. (2008) and McDonald et al. (2009). Therefore, a new GVP rate was calculated using only local nighttime hours. The adjusted GVP rate was 0.11 GVPs/hr using 7,307 night-hours between 2007 and 2019 (Figure 5).

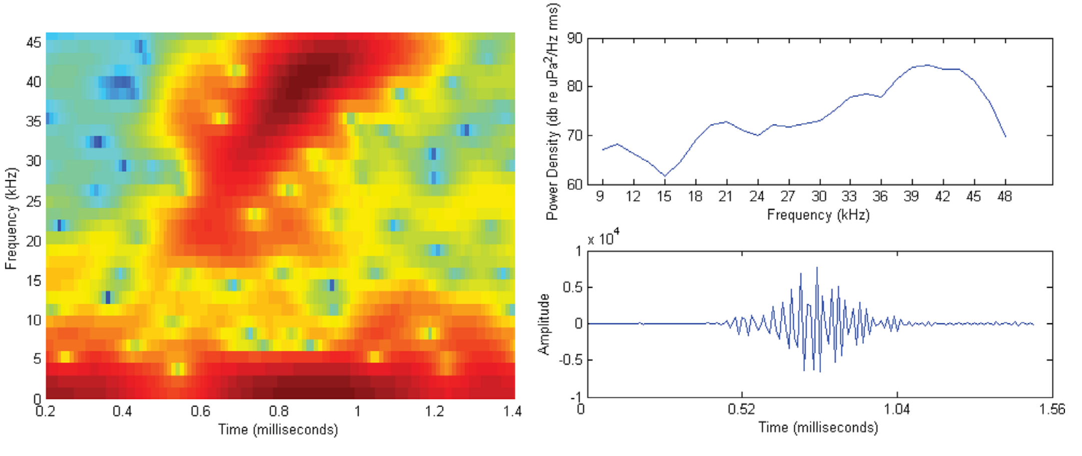

FIGURE 3 The left plot is a spectrogram of a BWC foraging pulse from PMRF, the top right plot is the spectral density, and the bottom right plot is the time series.

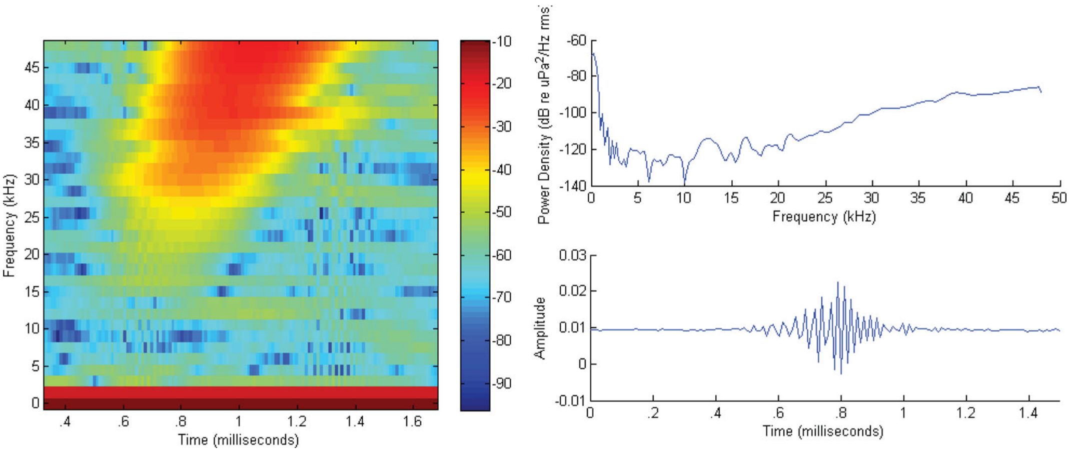

FIGURE 4 BWC foraging pulse from Cross Seamount with the spectrogram in the left plot, and spectrum level in top right plot and the time series in the bottom right plot (used with permission from McDonald, personal communication, December 2020). The Cross Seamount data were down-sampled from 192 kHz to the PMRF hydrophone sampling frequency of 96 kHz.

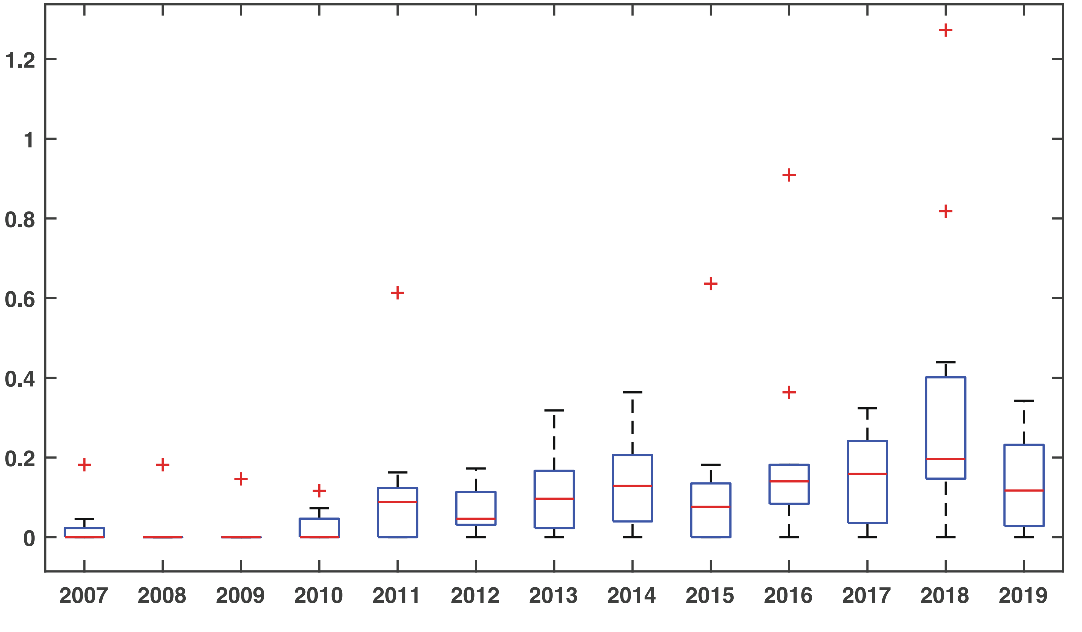

FIGURE 5 Boxplots of GVP rates for each year from 2006 to 2019. The red line is the median GVP/hr and the edges of the blue box are the 25th and 75th percentiles. Outliers are showed as red plus marks. See Table 1 for number of hydrophones used by year.

3.1 | Chi-square results

The median GVP depth was 958.7 m, with 50% of GVPs occurring between 750 m and 1,281 m, which was a noticeably smaller span of depths compared to the total hydrophone depth extent of 626 m to 4,825 m and median depth of 3,365 m (Figure 6). The median slope gradient where BWC beaked whales were found (median = 16%) was similar

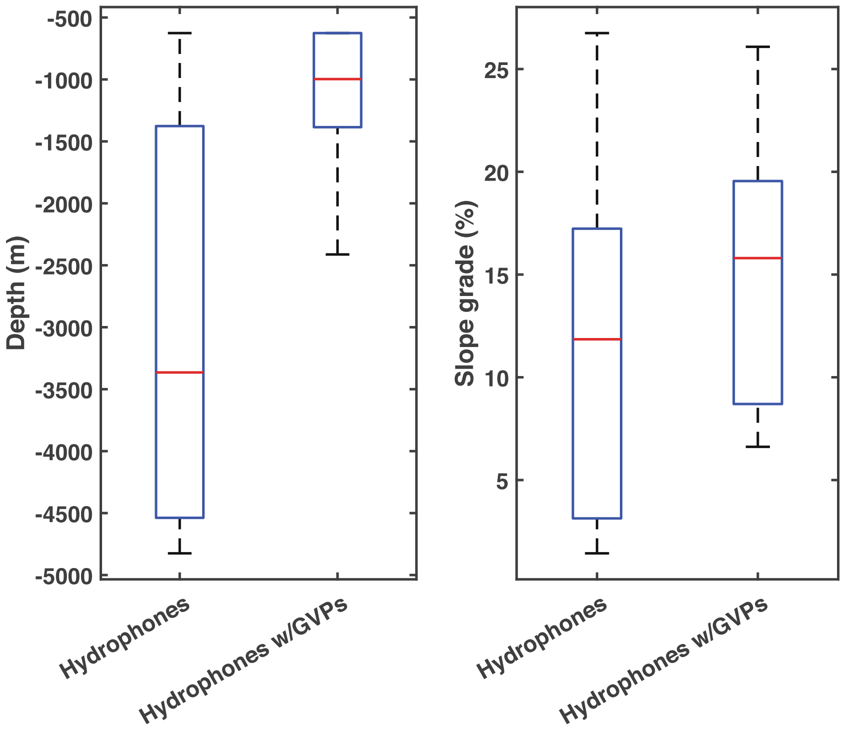

FIGURE 6 Boxplots of the depth of the 62 PMRF hydrophones used in this analysis versus the hydrophones with detected BWC beaked whale (left) and the slope gradient of all hydrophones versus hydrophones with detected BWC beaked whale (right). The red lines represent the median values and the edges of the bottom and top of the box are the lower and upper quartiles. The lower boxplot whisker is the nonoutlier minimum and the upper boxplot whisker is the nonoutlier maximum. Outliers are values that are more than 1.5 times the interquartile range (the distance between the top and bottom edges of the box) away from the top or bottom of the box.

to but slightly higher than the overall median across the range (median 12%) and the BWC beaked whale GVPs occur across a narrower breadth of slopes. BWC beaked whale GVP occurrence across discrete depth and slope measured at each hydrophone deviated significantly from expectations in chi-squared tests (depth: $\chi^2 = 1{,}979.8$, $p < .0001$; slope: $\chi^2 = 561.3$, $p < .0001$).

Seasonal trends resulting from chi-square tests indicated that there were slightly more observed than expected GVPs in the fall and winter than the spring and summer (Figure 7b, Table 2; $p = .035$). Breaking the year down further into the months showed statistically fewer GVPs than expected in May, June, August, and September and more GVPs than expected in October, January, and February (Figure 7c, Table 2; $p < .0001$). The diurnal analysis indicated that there were almost no GVPs detected from 0800 to 1600 HST; almost all dives were detected at night with a peak in the hours before dawn (Figure 7b, Table 2; $p < .0001$). An examination of the lunar cycle found there were more dives than expected during the first waning phase into the new moon phase (i.e., lunar illumination progresses from 33% to 0%) and fewer dives than expected during the full moon until the waning halfmoon (i.e., lunar illumination progresses from 100% to 50%) (Figure 7d bottom right, Table 2; $p < .001$).

3.2 | GAM results

GAMs were developed using a quasipoisson distribution to account for overdispersion, with a log link. No multicollinearity was found among the variables used in the final models. The final temporal model included the covariates Hour, Lunar Illumination, and an interaction term between the two, and had an explained deviance of

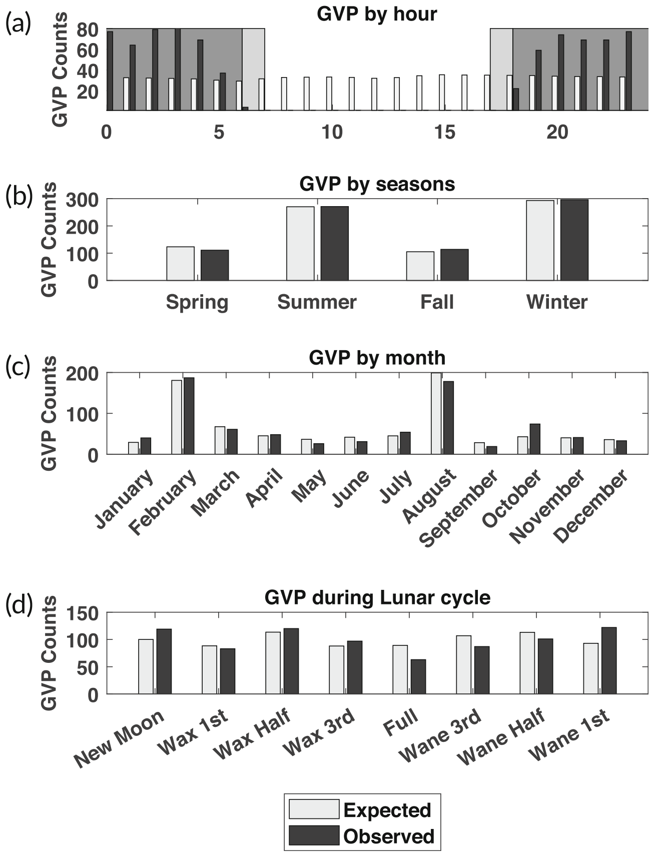

FIGURE 7 Chi-square results showing expected (light gray) versus observed (dark gray) GVPs from top (a) GVP by hour (nighttime hours from April to September indicated by dark gray shading, nighttime hours from October to May indicated by light gray shading), (b) seasons, (c) month, and (d) lunar cycle. Note that the increased dive count during February and August are a result of the increased recording effort due to SCCs taken place during those months. All data recorded from baseline and SCC events were used in the chi-square analysis.

TABLE 2 Chi-square test *p*-values.

Chi-square test	Chi-square value	*df*	*p*
GVP by season	8.5145	3	*.036*
GVP by month	41.015	11	*<.0001*
GVP by hour	892.35	23	*<.0001*
GVP by lunar cycle	26.96	7	*.0003*

Note. Significant *p*-values are italicized.

4.59% (Figure 8, Table 3). The temporal variables did demonstrate autocorrelation, so a corARMA was implemented within the GAM with the form set to 1 and the autoregressive order set to 3. Similar to the chi-square results, the interaction between hour and lunar illumination indicated there was a peak in dive activity at night during the new moon (lunar illumination 0%–20%), fewer dives during stronger lunar illumination, and no dives during the day. The spatial model included the variables Depth and Slope and had an explained deviance of 9.47% (Figure 9, Table 3).

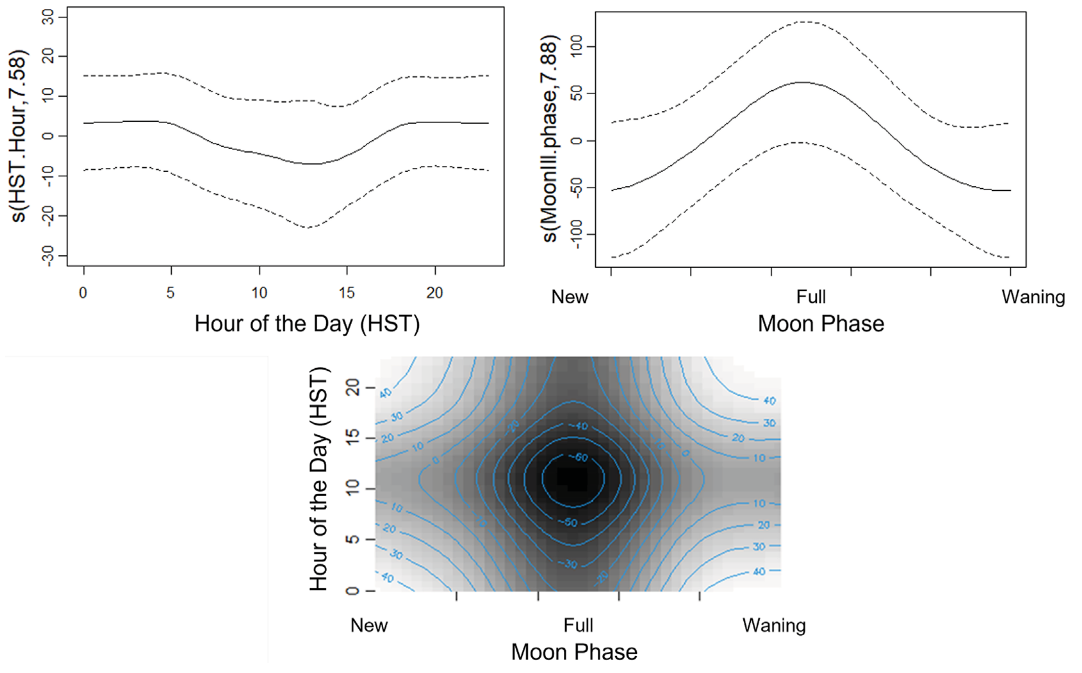

FIGURE 8 Smoothed predictor terms used in the temporal BWC beaked whale habitat model, with confidence intervals reflecting the standard error about the overall mean. The dashed lines represent the standard error about the mean. The interaction term is plotted as a contour, with light areas indicating higher likelihood of BWC beaked whale dive occurrence and dark areas indicating lower likelihood of BWC beaked whale dive occurrence.

TABLE 3 Test statistics (*F*-tests for all smoothed continuous covariates) and *p*-values for all covariates included in the spatial and temporal environmental models predicting the likelihood of BWC beaked whale GVPs at PMRF.

	Covariate	Test statistic value	*p*
Temporal model	Hour	8.61	*<.001*
	Lunar phase	8.79	*.018*
	Hour*Lunar phase Interaction term	17.51	.148
Spatial model	Hydrophone depth	4.99	*<.001*
	Hydrophone slope	7.00	*<.001*

Note. Significant *p*-values are italicized.

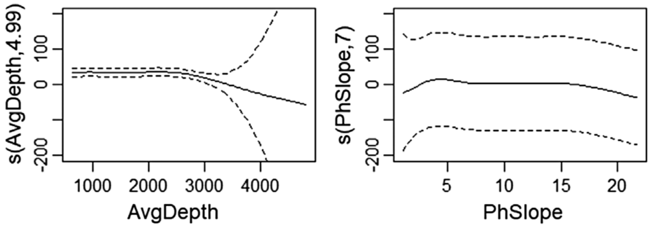

FIGURE 9 Smoothed predictor terms used in the spatial BWC beaked whale habitat model, with confidence intervals reflecting the standard error about the overall mean. The dashed lines represent the standard error about the mean.

3.3 | GVPs during Navy training events

BWC beaked whale GVPs were categorized as occurring during baseline or during Navy training events to observe any differences in dive trends. There were 75 BWC beaked whale GVPs detected during Navy training events from 2011 to 2018, in 2,283 recording hours (1,168 of the recording hours occurred during night and were utilized for BWC beaked whale GVP rate calculations). The number of observed BWC beaked whale GVPs was less than expected during Navy training activities given the recording effort (Figure 10a). An examination of the three-day periods before, during, and after Navy training events indicated that the observed BWC beaked whale GVPs were higher than expected before the SCCs and during baseline periods, but were lower than expected during, between, and after the SCC (Figure 10b). The median baseline nighttime BWC beaked whale GVP rate was 0.12 GVPs/hr for February and 0.09 GVPs/hr in August from 2011 to 2018, while the median nighttime GVP rate was 0.1 GVPs/hr in February and 0.07 GVPs/hr in August during SCC training events (Figure 11). The lower-than-expected presence of GVPs during Navy training events was statistically significant ($\chi^2 = 8.36$, $df = 2$, $p = .015$). When the training events were further separated into before, during, after, between (weekends), and no training events, the chi-square results were even more statistically significant ($\chi^2 = 16.41$, $df = 4$, $p = .0025$). The interquartile range of the depth distribution (25% to 75% quantiles) of BWC beaked whale GVPs during baseline occurred between 625 m and 1,512 m (median depth 997 m), while the depth distribution of BWC beaked whale GVPs during SCC training events was shifted to a shallower depth range of 625–1,092 m (median depth 959 m) (Figure 12).

In the GAM that included SCC Period (Before, During, Weekend, After, or None), the During phase had significantly fewer dives than the baseline (None) ($p < .001$), as did the dives over the weekend between phases and the after period ($p < .001$ for both periods; Figure 13). Although dives were reduced, this variable had a low overall

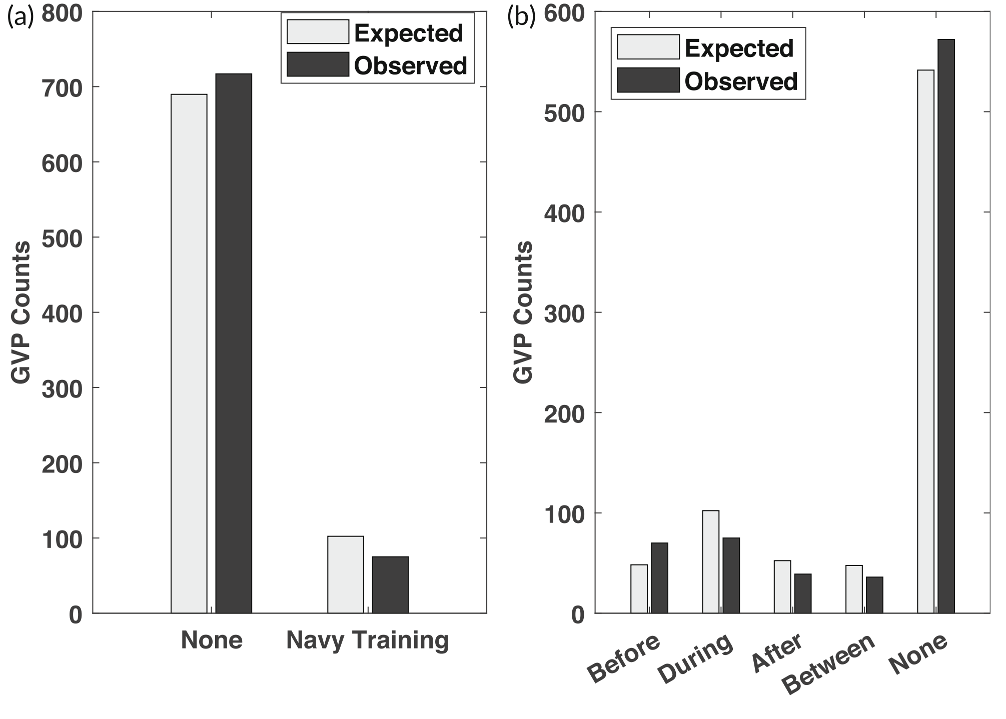

FIGURE 10 Chi-square test results showing expected and observed BWC beaked whale GVPs during: (a) Baseline versus Navy Training (left) and (b) for BWC beaked whale GVPs examined by periods Before, During, After, and Between Navy training or during Baseline (right).

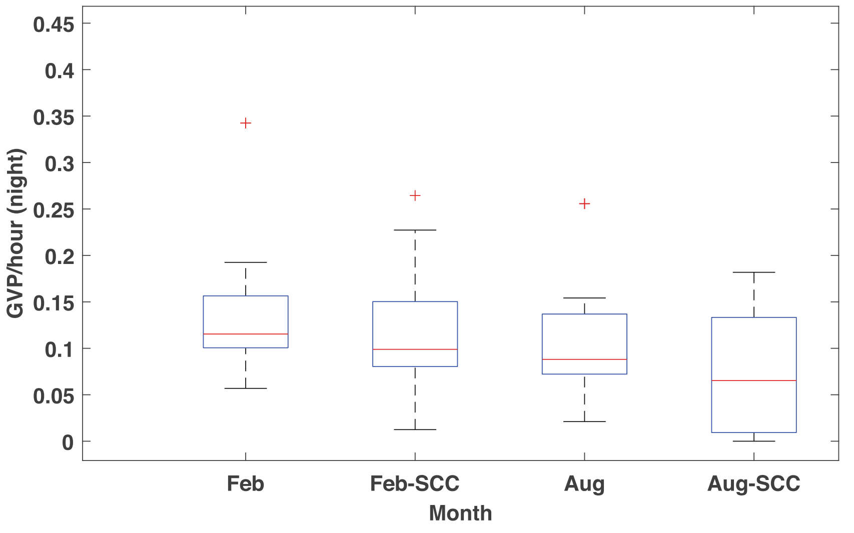

FIGURE 11 Boxplots of BWC beaked whale GVP rates during baseline and during SCC for February and August from 2011 to 2018. The red line is the median value and the edges of the bottom and top of the box are the lower and upper quartiles. The lower boxplot whisker is the nonoutlier minimum and the upper boxplot whisker is the nonoutlier maximum. Outliers are values that are more than 1.5 times the interquartile range (the distance between the top and bottom edges of the box) away from the top or bottom of the box.

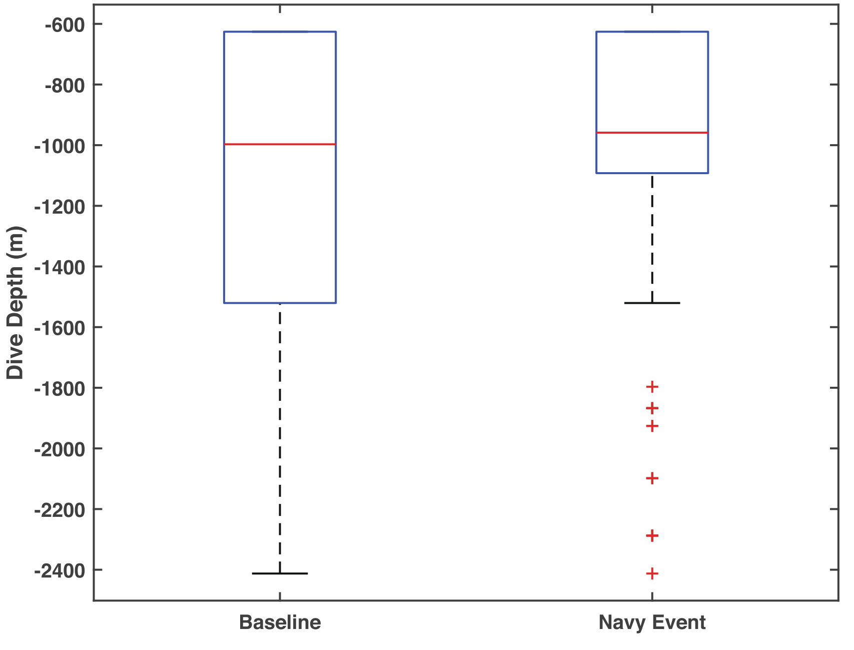

FIGURE 12 Boxplots of the depth of PMRF hydrophones with detected BWC beaked whales during baseline and during Navy training. The red line is the median value and the edges of the bottom and top of the box are the lower and upper quartiles. The lower boxplot whisker is the nonoutlier minimum and the upper boxplot whisker is the nonoutlier maximum. Outliers are values that are more than 1.5 times the interquartile range (the distance between the top and bottom edges of the box) away from the top or bottom of the box.

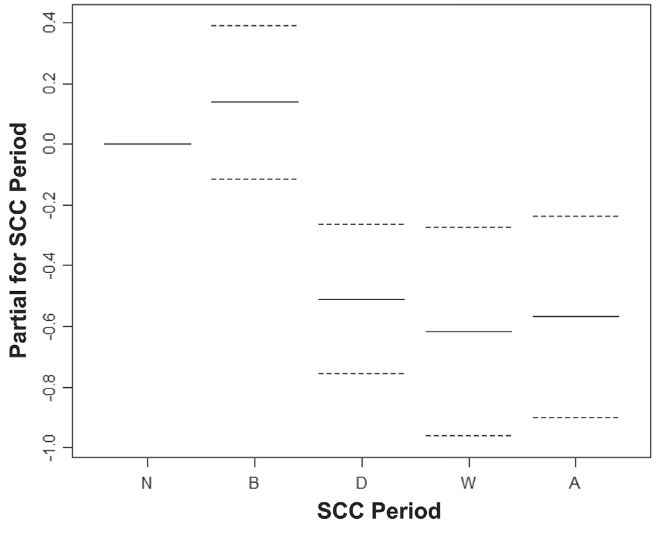

FIGURE 13 Partial effects of the parametric model component of SCC period on the likelihood of BWC beaked whale dive occurrence. None/Baseline (N), up to three days Before (B), During Phase A or Phase B (D), on the weekend between the phases (W), or up to three days After (A), where None was held as the reference level. All phases had significantly less dives than the baseline period except for the Before phase. The dashed lines represent the standard error about the mean.

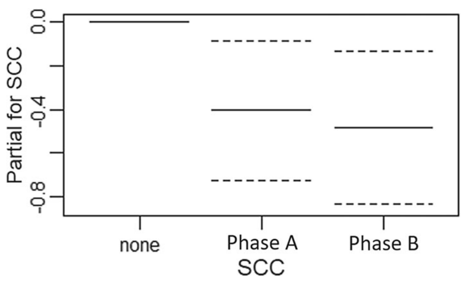

FIGURE 14 Partial effects of the parametric model component of SCC Phase (None/Baseline, Phase A, Phase B) on the likelihood of BWC beaked whale dive occurrence. The baseline level was held as the reference level. The dashed lines represent the standard error about the mean.

impact on BWC beaked whale dive behavior, with <1% explained deviance. Similarly, in the model that included SCC Phase (None, Phase A, Phase B) dives were reduced during both Phase A and Phase B (Figure 14; $p = .012$ and .006, respectively; Table 4), but the contribution of this variable to BWC beaked whale overall dive behavior was also very small, again with less than 1% explained deviance.

4 | DISCUSSION

From the long-term analysis at PMRF, there were 14,446 total hours recorded over 13 years, and 792 detected BWC beaked whale GVPs. The statistical modeling results demonstrated that BWC beaked whales forage within a small area at PMRF, primarily near the island where water depths range from 626 to 1,385 m and the seafloor slope ranges from 9% to 20% gradation (Figure 6); these are common habitat features for beaked whale species. Near

TABLE 4 *t*-test statistics and *p*-values for the parametric coefficients of SCC Phase and SCC Period (included in separate models). The baseline (None) period was held as the reference level in both cases.

Model	Covariate	*t*-test statistic	*p*
SCC Phase	SCC Phase A	−2.52	*.012*
	SCC Phase B	−2.74	*.006*
SCC Period	Before SCC	1.09	.28
	During SCC	−4.15	<*.001*
	Weekend between phases	−3.58	<*.001*
	After SCC	−3.44	<*.001*

Great Abaco in the northern Bahamas, Blainville's beaked whales were mostly detected foraging in water depths between 136 and 1,319 m with seabed slopes between 68 and 296 m/km (7%–30% gradation), which may be where typical beaked whale prey is concentrated (MacLeod & Zuur, 2005). In the Mediterranean Sea, Cuvier's beaked whale presence was the highest from 756 to 1,389 m and seafloor slope between 31 and 51 m/km (3%–5% gradation; Moulins et al., 2007). Cuvier's beaked whales at SOAR were sighted in water depths ranging from 1,045 to 1,741 m (M = 1,580 m, SD = 138) and bathymetry ranging from 0 to 17 degrees, with a median of 1% gradation (Falcone et al., 2009). While those values are similar across species and locations, off Hawai'i Island, where both species cooccur, Cuvier's beaked whales are found in areas almost twice as deep (grand median = 2,333 m) as Blainville's beaked whales (grand median = 1,155 m; Baird, 2019).

Almost all BWC beaked whale GVPs were detected between dusk and dawn, with a mean GVP rate of 0.11 GVPs/hr (night-time hours only). In a comparison between several beaked whale species that were acoustically detected across different sites, Baumann-Pickering et al. (2014) found diel patterns only with BWC beaked whale detections. It is possible that this strict timing is due to a specific prey preference that is only available or is far more accessible at night. From acoustic recordings at PMRF, Blainville's beaked whales were detected almost equally day and night in Hawaiian waters (Henderson et al., 2016). Satellite tagged Cuvier's beaked whales in southern California also demonstrated little variation in foraging dive depth and duration between night and day, which suggests that their prey does not have a diel pattern (Schorr et al., 2014), although there were slightly more dives that occurred at night (Barlow et al., 2020). However, it is also unknown if beaked whales hunt for different deep-diving prey at different times of the diel cycle (Baird et al., 2008).

GAM modeling results and chi-square tests of the lunar cycle indicated that BWC beaked whales also appeared to forage more during low lunar illumination (i.e., approximately around the new moon phase) at PMRF (Figures 7 and 8). This is contrary to the analysis by Henderson et al. (2016) of Blainville's beaked whales that had more GVPs detections at night during the full moon than during the new moon, and the tagged Blainville's beaked whale whose foraging dive depths were shallower during the new moon and increased in depth with the fraction of lunar illumination (Baird, 2019). Henderson et al. (2016) and Baird (2019) both hypothesized that this preference could be due to the Blainville's beaked whales' prey's vertical movement due to the lunar phases. Cuvier's beaked whale dives also have a relationship to lunar illumination, such that they avoid near surface depths in strong moonlight (Barlow et al., 2020). The decrease of near surface dives during the daytime and during nights of high moonlight is hypothesized to be a dive strategy to avoid visual detection by predators (Baird et al., 2008; Barlow et al., 2020). It is not known why BWC beaked whales may forage more during low lunar illumination, but because they are only detected at night and conduct more foraging dives during low light conditions, their dive behavior could be the opposite of Cuvier's and Blainville's beaked whales and they could be hunting different prey that do not migrate in response to the lunar phases. However, further research into BWC beaked whale dive depth patterns is needed, including actual foraging dive depths and their behavior during dives, especially during the day.

The number of BWC beaked whale GVPs occurred significantly more than expected based on the number of hours of recording in 2011, 2018, and 2019. This was likely the result of the increase in the number of recorded hydrophones and recorder sensitivity starting in 2011, and a change in hydrophone configuration to an increased number of hydrophones recorded in the southern part of the range starting in 2018. Therefore, it should not be concluded that BWC beaked whale dive rates increased in those years, rather that the acoustic coverage at ideal BWC beaked whale foraging habitats was improved. However, dives were consistently detected at rates higher than expected in the fall, particularly in October. This could indicate some seasonality in the occurrence of BWC beaked whales at PMRF.

Data were also collected and analyzed from February and August Navy training events at PMRF to determine any changes in dive patterns associated with Naval training activity and the use of MFAS. There was a total 75 BWC beaked whale GVPs detected during 16 SCC events between 2011 and 2018. When BWC beaked whale GVPs and recording effort were concurrent with Naval training events versus baseline periods, mean GVP rates decreased from 0.26 GVP/hr to 0.083 GVP/hr in February and 0.14 GVP/hr to 0.012 dives/hr in August. The median BWC beaked whale GVP depth did not change much between Navy training events and baseline, but the distribution of GVP detections skewed in favor of shallower depths during Navy training events compared to baseline (Figure 12). Most of the Navy training exercises utilized the central part of the range, which explains the shift to more GVPs detected on shallower hydrophones during training events, as has also been observed for Blainville's beaked whales (Manzano-Roth et al., 2016). The GAM results were statistically significant for the training events periods, indicating that there were fewer GVPs detected during and between (weekends) events (Figure 13). These results show that the BWC beaked whale activity decreased during training and remained at reduced levels up to 3 days after the training was over.

Long term data from PMRF data was previously utilized to analyze Blainville's beaked whale habitat use and GVP dive occurrences (Henderson et al., 2016). While Blainville's beaked whales GVPs were also detected at the same time as some BWC beaked whale GVPs on the PMRF range, Blainville's beaked whale GVPs were detected throughout the 24 hr diel cycle and were detected more often during the full moon phase (Henderson et al. 2016). Blainville's beaked whales had a much higher overall GVP rate of 2.1 dives/hr compared to the nighttime dive rate of 0.11 GVP/hr for BWC beaked whales. They prefer habitats with means of around 2,000 m depth and 15% slope, which was deeper than the BWC beaked whale preferred area of the PMRF, but similar in bathymetry inclination. Finally, Blainville's beaked whales also demonstrated decreased foraging activity on the range during Navy training exercises.

It is still unknown whether the BWC foraging pulse is from an as-yet unidentified beaked whale such as the Ginkgo-toothed beaked whale (*Mesoplodon ginkgodens*) or from a known species (e.g., Blainville's beaked whales) with an adapted novel foraging pulse for night-time foraging. Baumann-Pickering et al. (2013) theorized that the BWC foraging pulse has strong similarities to the BWG signal found in the Atlantic Ocean, and both signals could be the from same species spanning both oceans, or two species could have converged on a similar signal. The acoustic analysis presented here suggests that the BWC beaked whale population at PMRF may be sparse, with low dive rates that occur only at night. The results from this study could be beneficial for future marine mammal surveys that may be interested in targeting and identifying this species by focusing on where and when individuals are most likely to be present at PMRF. In addition to identifying the species that produces the BWC foraging pulse, future BWC beaked whale analyses could include density estimation, GVP duration estimation, and dive pattern comparisons with additional beaked whale species at PMRF such as Cuvier's or Longman's beaked whales.

In conclusion, foraging echolocation pulses were detected on hydrophones at PMRF, off the coast of Kaua'i, Hawai'i, that matched foraging pulses of the beaked whales first acoustically identified at Cross Seamount, Hawai'i. BWC beaked whale GVPs were consistently detected throughout data collected from 2007 to 2019, and therefore may be a resident, or at least commonly occurring, population at PMRF. Like other beaked whales on the range, the BWC beaked whale responded to MFAS on the range by decreasing foraging dives during training activity but returned to baseline levels after training events. If the BWC beaked whale is an unidentified species, it is a unique beaked whale species that only feeds at night; however, the advantages of foraging only at night are unknown and should be investigated further.

AUTHOR CONTRIBUTIONS

Roanne Manzano-Roth: Formal analysis; investigation; methodology; validation; visualization; writing – original draft. **E. Elizabeth Henderson:** Conceptualization; formal analysis; funding acquisition; investigation; methodology; supervision; validation; visualization; writing – review and editing. **Gabriela C. Alongi:** Data curation; formal analysis; investigation; software; validation; writing – review and editing. **Cameron R. Martin:** Visualization. **Steve W. Martin:** Supervision; writing – review and editing. **Brian Matsuyama:** Software.

ACKNOWLEDGMENTS

This research was completed as part of the Whale Acoustics Reconnaissance Project and the Navy Marine Species Monitoring Program, with financial support for this analysis provided by Julie Rivers at Commander Pacific Fleet. The authors would also like to thank personnel at PMRF for their assistance in recording the acoustic data, which was essential to this study, particularly Jim Hager, John Winsley, Eliseo Boloson, Bryson Kurokawa, Ileana Muñoz, and Robin Higuchi.

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How to cite this article: Manzano-Roth, R., Henderson, E. E., Alongi, G. C., Martin, C. R., Martin, S. W., & Matsuyama, B. (2023). Dive characteristics of Cross Seamount beaked whales from long-term passive acoustic monitoring at the Pacific Missile Range Facility, Kauaʻi. *Marine Mammal Science*, *39*(1), 22–41. https://doi.org/10.1111/mms.12959