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Classification of Bering-Chukchi-Beaufort Bowhead Whale Calls

Alexander J. Hare[1,2] | William D. Halliday[1,2] | Nikoletta Diogou[1,2] | Stan E. Dosso[1] | Bridgette Nzomwita[1] | Humfrey Melling[3] | Andrea Niemi[4] | Xavier Mouy[5,6] | Stephen J. Insley[2,7]

[1]School of Earth and Ocean Sciences, University of Victoria, Victoria, British Columbia, Canada | [2]Wildlife Conservation Society Canada, Whitehorse, Yukon Territories, Canada | [3]Institute of Ocean Science, Fisheries and Oceans Canada, Sidney, British Columbia, Canada | [4]Arctic Region, Fisheries and Oceans Canada, Winnipeg, Manitoba, Canada | [5]JASCO Applied Science Ltd, Victoria, British Columbia, Canada | [6]Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA | [7]Department of Biology, University of Victoria, Victoria, British Columbia, Canada

Correspondence: Alexander J. Hare (alexharebiology@gmail.com)

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ABSTRACT

Bowhead whales (*Balaena mysticetus*) are an endemic species to the Arctic Ocean and are highly reliant upon acoustic communication. Despite being one of the most thoroughly studied populations of bowhead whales, we still have a poor understanding of the calling behavior of Bering-Chukchi-Beaufort (BCB) bowhead whales. In order to address this knowledge gap, we extracted 2326 bowhead whale calls from passive acoustic recordings taken between 2018 and 2021 at eight bottom-mounted hydrophone recording sites across the eastern Beaufort Sea and Amundsen Gulf. Using a random forest model, we classified eight distinct call categories based on 16 acoustic features with 86% accuracy. We present descriptive statistics for these different call categories, highlighting the most important acoustic features used in differentiating between them. By quantitatively describing these calls and defining the vocal repertoire of BCB bowhead whales, this study lays important groundwork for examining the acoustic ecology of this highly vocal marine species. These results provide a basis to test hypotheses regarding the association of various calls and behaviors in order to assess call function, as well as building an acoustic morphology database for future call detectors and dialect comparison with other bowhead whale populations.

1 | Background

When interacting with each other, many animals produce acoustic signals referred to as calls that convey specific contextual meaning (Bradbury and Vehrencamp 2011). In line with source-filter theory (Taylor and Reby 2010; Tokuda 2021), calls often contain cues relating to individual morphology (Rendall et al. 2005), sex (Volodin et al. 2015), or latent physiological state (Hare et al. 2024), potentially allowing receivers to extract relevant information and alter their own behavioral patterns (Danchin et al. 2004). For example, in red deer (*Cervus elaphus*), the minimum formant frequencies of stag roaring provide honest information to receiving females regarding the age and body size of the calling stag, both factors directly related to reproductive success and individual fitness (Reby and McComb 2003). Further, in southern elephant seals (*Mirounga leonina*), the frequency of the 4th and 5th formants as well as formant dispersion of male aggressive vocalizations provide reliable information regarding body size and resource holding potential of the calling individual (Sanvito et al. 2007).

Beyond the potential for latent individual features to be conveyed in the acoustic structure of calls, specific calls often carry contextually relevant information (Marler 1955). The most basic piece of information contained within calls is often identity, such as in the pulsed contact calls of beluga whales (*Delphinapterus leucas*) that vary reliably between individuals

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(Morisaka et al. 2013). Beyond these individual differences in cetacean calls, the use of acoustic signals can range from advertisement of reproductive receptivity, as observed in the singing of humpback whales (*Megaptera novaeangliae*) (Herman 2017), to the echolocation clicks used for foraging in odontocetes such as the beluga whale (Panova et al. 2012). Further, information regarding social grouping and membership can be conveyed. For instance, matrilineal inheritance of call repertoire has been demonstrated in killer whales (*Orcinus orca*) (Yurk et al. 2002), and the coda vocalizations of sperm whales (*Physeter macrocephalus*) (Gero et al. 2016). This social transmission of acoustic behavior is most apparent and dramatic in the complex singing behavior of baleen whales (Janik 2009). In examining differences in the type of call produced and structural variation within calls, we are able to gain insights into the ecology and behavior of animals that it would otherwise be difficult to observe.

Among the emerging tools to study acoustic variation in calls, passive acoustic monitoring (PAM) has shown great potential for addressing difficult ecological questions (Gibb et al. 2019; Hoefer et al. 2023). By using hydrophones to record the soundscape over long periods of time, spanning multiple months to years, we are able to collect large bioacoustic datasets in remote locations at relatively low costs (Shonfield and Bayne 2017; Sousa-Lima 2013). These data can then be used to measure a range of important ecological factors, such as community biodiversity, migration timing, and space use, as well as the impacts of anthropogenic activity on acoustically sensitive species (Blumstein et al. 2011). For example, using PAM, Halliday et al. (2019) were able to quantify the impact of vessel exposure on beluga whale vocal behavior in the Mackenzie River estuary, demonstrating a distinct decrease in calling rates during vessel transits. Studies such as these are important, as the recent increase in vessel traffic throughout the Canadian Arctic due to declining summer sea-ice (Årthun et al. 2021; Dawson et al. 2018; Rodríguez et al. 2024) poses a distinct threat to acoustically-sensitive Arctic endemic species such as the bowhead whale (COSEWIC 2009).

Bowhead whales are the only endemic baleen whale to the Arctic (George et al. 2021) and have distinct cultural importance to Inuit (Gadamus 2013; Huntington et al. 2015). Following near-extinction at the beginning of the 20th century due to commercial whaling, the Bering-Chukchi-Beaufort (BCB) population of the western Canadian Arctic has rebounded from approximately 1000 individuals to over 16,000 individuals in just over a century (Baird and Bickham 2021). While commercial whaling is no longer a threat, bowheads' dependence on their acoustic environment for communication and navigation (Clark and Johnson 1984; George et al. 1989) implicates rapidly increasing noise levels in the Arctic as a distinct threat to this population (COSEWIC 2009). This is of particular concern with the recent increase of vessel traffic throughout the Northwest Passage (Dawson et al. 2018), which is only expected to increase in the coming decades due to climate change (Boylan 2021). Indeed, multiple studies have highlighted areas of concentrated overlap between BCB bowhead whales and vessel traffic, particularly during their summer foraging and autumn migration (Halliday et al. 2018, 2021, 2022; Martin et al. 2023; Szesciorka et al. 2026).

Currently, PAM has been successfully utilized in studying the ecology and behavior of bowhead whales, describing migration (Clark et al. 2015; Szesciorka et al. 2024), overwintering behavior (Insley et al. 2021), and the acoustic repertoire of song calls for the Spitsbergen population (Thomisch et al. 2022). Bowhead whale calls can be largely grouped into song and nonsong calls. Songs have been described in a few studies (Johnson et al. 2015; Stafford et al. 2018, 2008; Tervo et al. 2009; Thomisch et al. 2022) and have been largely described as being quite variable, changing within a season and across years. They are also thought to be produced primarily by males, likely facilitating both female reproductive selection and assessment of the competitive abilities of other males (Delarue et al. 2009; Stafford et al. 2008; Tervo et al. 2009). Unlike songs, calls are thought to be produced by both females and males. The nonsong call categories of bowhead whales are thought to be much more static and stereotyped than song calls and have largely been documented in previous work (see Stafford and Clark 2021 for a review) and are described as down sweeps, up sweeps, flat tonal signals, and modulated down sweeps (Clark and Johnson 1984). These calls are produced across seasons, occurring both during migration (Blackwell et al. 2009) and summer feeding in Arctic waters (Charif et al. 2013). Further, the repertoire of calls appears to be frequently incorporated into the syntax of song phrases (Thomisch et al. 2022), and, as such, understanding their diversity has broad implications to understanding social communication in this species.

Despite previous documentation of calling behavior within the BCB population, we still have a poor understanding of the behavioral function of calls (Stafford and Clark 2021), with hypotheses ranging from maintaining contact between conspecifics (Clark et al. 1986) to acoustically evaluating ice density (George et al. 1989). While formalized classification models have been applied to the social calls of southern right whales (*Eubalaena australis*) (Webster et al. 2016) and the song formants of both Eastern Canada-West Greenland (ECWG) (Tervo et al. 2009) and Spitsbergen populations of bowhead whales (Thomisch et al. 2022), a formalized model has not been applied to the nonsong calls of any bowhead population. Given the prevalence of referential calling across vertebrate taxa, where the characteristics of calls are used to convey information to conspecifics regarding relevant environmental events (Gill and Sealy 2004; Manser et al. 2002; Seyfarth et al. 1980), the complex acoustic behavior of bowhead whales (Stafford and Clark 2021), and the distinct possibility of social learning influencing call structure (Garland et al. 2025), classifying and quantifying BCB bowhead whale calls represents a fundamental tool in understanding the ecology and behavior of this species. By generating a quantitative BCB bowhead whale call repertoire, we can begin to explore potential differences in dialect across major populations and assess how climate change and anthropogenic noise impact this culturally and ecologically important species. In our current study, we address this knowledge gap using a large PAM dataset collected from within the Inuvialuit Settlement Region of the western

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Canadian Arctic, classifying the simple nonsong calls produced by BCB bowhead whales in their summer foraging areas.

2 | Methods

2.1 | Source Data

Passive acoustic data were collected between 2018 and 2021 from eight sites in the eastern Beaufort Sea and Amundsen Gulf (Figure 1) using bottom-mounted moorings equipped with Ocean Instruments Sound Trap ST500 or ST600 STD recording devices (Ocean Instruments, NZ). All recorders were deployed on a high gain setting with a sampling rate of 48 kHz on a duty cycle of either 5 min on every hour or 5 min on every half-hour depending on the deployment year (Table 1). Recordings from these deployments were then processed using a bowhead whale call detector and classifier (Spectro Detector; JASCO Applied Science Ltd., Victoria, British Columbia, Canada) (Diogou et al. 2023; Moloney et al. 2014; Mouy et al. 2013) to identify potential bowhead whale vocalizations. In brief, this detector calculates and normalizes spectrograms for each frequency band between 10 Hz and 8 kHz. It then segments each normalized spectrogram to identify acoustic events, which are then classified as either beluga whale (*Delphinapterus leucas*), bearded seal (*Erignathus barbatus*), or bowhead whale using a random forest model (Mouy et al. 2013). All potential bowhead vocalizations flagged by the detector were then reviewed by a bioacoustic analyst (ND) as spectrograms in Raven Pro software (Version 1.6.5, Cornell Lab of Ornithology, Ithaca, NY, USA) using a Hann window at a size of 7000 samples with 90% overlap, and at a frequency range of 0–700 Hz and a time range of 18 s. Identifications were then verified by an expert analyst (WH) to confirm positive species identification.

2.2 | Feature Extraction and Call Selection

A total of 40,401 positively identified bowhead calls were then processed and reviewed by the primary analyst for this study (AH) according to the following methods. First, any calls that were considered low certainty by the first two analysts were removed from the dataset, then any calls with a signal to noise ratio (SNR) < 10 dB re 1 μPa as identified by the automated SNR calculation within each selection box in Raven Pro were removed. All remaining calls were reviewed by either the primary analyst or assistant analyst (BN) to assign manual call categories, more accurately define selection boxes, extract acoustic features for analysis, and assess subjective quality as the automated SNR detection sometimes struggled separating the actual signal from competing sound sources. During this review period, the analysts grouped all calls into one of 10 distinct call categories (Table 2) based upon pre-defined spectral features associated with existing call categories within the broader literature (Clark and Johnson 1984; George et al. 1989; Sawyer 2024; Stafford and Clark 2021).

Due to the nature of single-sensor based PAM, we are unable to assess the identity, range, and full source-level spectral properties of each call (Gibb et al. 2019), so we chose to focus our analysis on the features of the received fundamental frequency of calls. Further, any complex vocalizations that featured biphonation (Clark and Johnson 1984) or song phrase units were omitted from our analysis, since these calls are thought to be much less stereotyped (Diogou et al. 2023), and we focused on simple calls that are produced throughout the

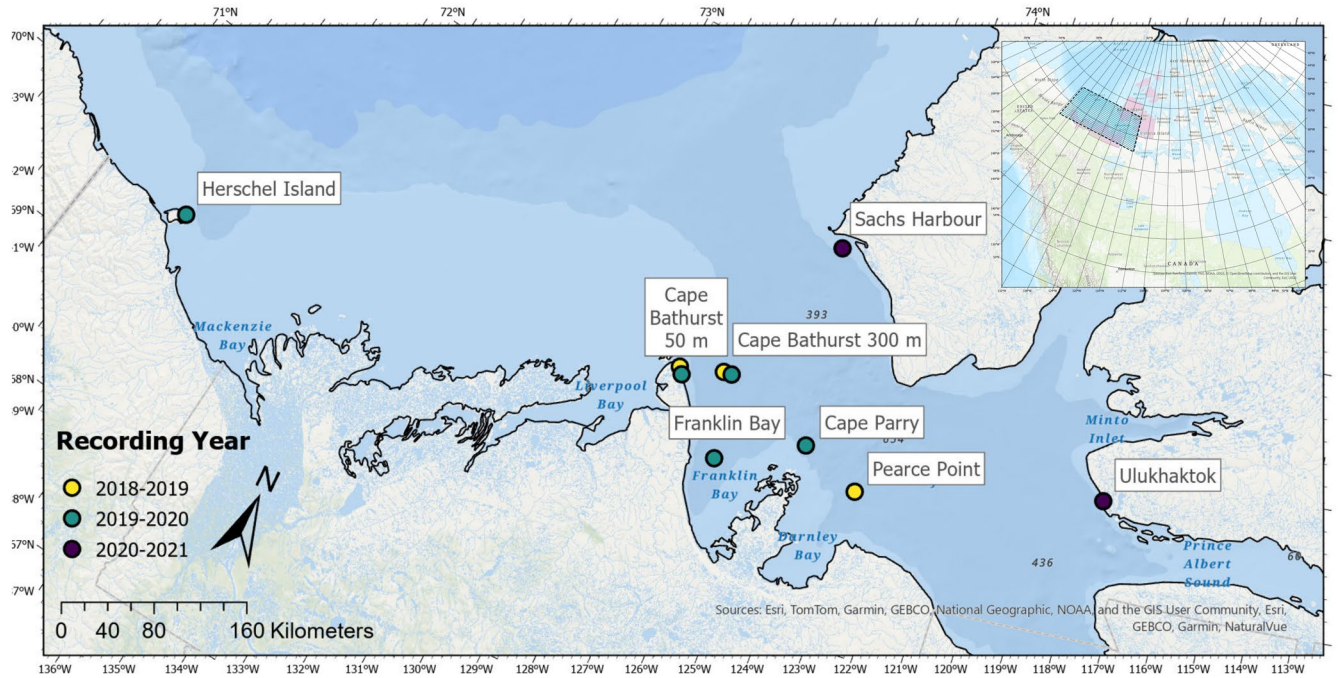

FIGURE 1 | Distribution of eight PAM moorings across the eastern Beaufort Sea and Amundsen Gulf from over three recording periods, 2018–2019 (yellow), 2019–2020 (green), and 2020–2021 (purple). Inset shows a global perspective highlighting our study area in the blue polygon with the Inuvialuit Settlement Region highlighted in pink.

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TABLE 1 | Passive acoustic recording parameters and the number of manually reviewed bowhead whale (*Balaena mysticetus*) vocalizations both prior to and following application of quality filtering for spectral analysis.

Site	Location	Season	Deploy date	Retrieval date	Recorder depth (m)	Duty cycle (minutes on/ minutes off)	Sampling rate (kHz)	End-to-end sensitivity (re 1 V/μPa)	Number of potential calls	Number of calls following filtering
Cape bathurst (50 m)	70° 34.55′ N, 127° 39.63′ W	2018–2019	2018-10-07	2019-09-27	43.5	5/55	48 kHz	−173.8	2665	460
Cape bathurst (300 m)	70° 40.87′ N, 126° 52.30′ W	2018–2019	2018-09-30	2019-09-27	289.5	5/55	48 kHz	−173.7	1678	467
Pearce point	70° 12.06′ N, 123° 09.47′ W	2018–2019	2018-10-02	2019-09-28	348	5/55	48 kHz	−174.2	1489	272
Cape bathurst (50 m)	70° 34.596′ N, 127° 39.642′ W	2019–2020	2019-09-27	2020-09-19	45	5/55	48 kHz	−175.9	757	37
Cape bathurst (300 m)	70° 40.872′ N, 126° 52.308′ W	2019–2020	2019-09-28	2020-09-20	290	5/55	48 kHz	−175.6	9806	113
Cape parry	70° 23.616′ N, 124° 32.406′ W	2019–2020	2019-09-28	2020-09-18	147	5/55	48 kHz	−175.7	1332	299
Franklin bay	70° 2.436′ N, 126° 18.402′ W	2019–2020	2019-09-27	2020-09-18	211	5/55	48 kHz	−177.3	4721	78
Herschel island	69° 39.306′ N, 138° 55.266′ W	2019–2020	2019-10-03	2020-09-29	38	5/55	48 kHz	−175.3	9625	527
Sachs Harbour	71° 52.27′ N, 125° 29.01′ W	2020–2021	2020-09-16	2021-08-22	45	5/25	48 kHz	−175.3	1375	11
Ulukhaktok	70° 42.03′ N, 117° 47.03′ W	2020–2021	2020-08-05	2021-07-20	33	5/25	48 kHz	−175.7	10,606	73

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TABLE 2 | The 10 initial bowhead whale (*Balaena mysticetus*) call categories identified by manual observers and the specific defining characteristics of each category.

Call label	Defining characteristics
Constant (CST)	• <20 Hz variation in F_0 across their duration
Up-sweep (USW)	• ≥ 20 Hz increase in F_0 across the duration of the call • No meaningful inflection points
Modified up-sweep (USW)	• ≥ 20 Hz increase in F_0 across the duration of the call • Single inflection point near the maximum fundamental frequency • F_0 decreases $<20\%$ of the observed range in F_0 following inflection point
Down-sweep (DSW)	• ≥ 20 Hz decrease in F_0 across the duration of the call • No meaningful inflection points
Modified down-sweep (MDS)	• ≥ 20 Hz decrease in F_0 across the duration of the call • Single inflection point near the maximum fundamental frequency, • F_0 increases less than 20% of the observed range in F_0 prior to the inflection point
Growl (GWL)	• Low frequency call often <400 Hz • Minimal frequency modulation • 2–4 strong harmonics
Honk (HNK)	• Typically, <1 s in duration • $F_0<200$ Hz • Numerous harmonics spanning multiple kHz
Pulsed (PLS)	• Multiple kHz bandwidth • Lack of a clear F_0 and harmonics
Concave (CAV)	• >20 Hz initial decrease in F_0 • ≥ 1 inflection point • Increases $\geq 20\%$ of the range in F_0 following inflection points
Convex (VEX)	• >20 Hz initial increase in F_0 • ≥ 1 inflection point • Decreases $\geq 20\%$ of the range in F0 following inflection points

year between conspecifics (Stafford and Clark 2021). Call category was largely determined by changes in the fundamental frequency, F_0, across the duration of the call as well as the number of inflection points, where the sign of the time derivative (slope) of F_0 changed as a function of time. Each of these initial call categories and the features that define them are highlighted in Table 2.

Acoustic features were extracted from each call using a combination of automatic feature extraction associated with the selection box used to annotate calls in Raven Pro, and through manual coding (Table 3). In brief, the fundamental frequency contour, which tracked changes in the inferred fundamental frequency across the duration of each call, was characterized using four point-selections within each selection box, highlighting: (1) fundamental frequency at the start of the call, (2) fundamental frequency at the end of the call, (3) minimum fundamental frequency of the call, and (4) maximum fundamental frequency of the call. These four points were then used to infer a number of spectral features through simple mathematical functions based on their relative position and magnitude of change between different combinations of the four points (Table 3). For example, to determine the minimum and maximum F_0 positions, we calculated at what point in the call each value occurred relative to the entire duration of the call and expressed it as a proportion of the duration. In addition to the features derived from these four points, both the number of harmonics, defined as the number of formants that were present at multiples of the fundamental frequency, as well as the number of inflection points, defined as an instance where the sign of the time derivative of F_0, were also coded from the spectrogram and through aural examination. These 16 automated and manually extracted features, described in detail in Table 3, were then retained for subsequent analysis.

Finally, for each call reviewed, we assessed call quality following the methods of Chmelnitsky and Ferguson (2012). In brief, we assigned each call to one of four subjective quality levels (1–poor, 2–medium, 3–high, and 4–excellent) based on the visual clarity of the spectrogram, aural clarity of the recording, and a lack of competing sound sources that would bias feature extraction. Only medium to excellent quality calls were retained for analysis. Due to the adjustment of selection boxes in Raven Pro during feature extraction, the SNR of these further filtered calls ranged from 9.58 to 29.12 dB re 1 μPa (see Supplementary Figure 1). Due to the limited number of honk ($n=23$) and pulsed ($n=22$) calls observed, representing 1% and 0.9% of all reasonable quality calls respectively, these call classes were removed from the final dataset, bringing the total number of calls analyzed to 2326 medium or higher quality

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TABLE 3 | Detailed description of manual and automated features extracted from bowhead whale (*Balaena mysticetus*) calls.

Feature	Shorthand	Description	Unit	Extraction method
Delta frequency	ΔF	Change in mean frequency across the duration of the selected call	Hz	Raven Pro
Peak frequency	F_{peak}	Maximum frequency detected within selected call	Hz	Raven Pro
Minimum entropy	E_{min}	Lowest entropy level detected across duration of selected call	Bits	Raven Pro
Maximum entropy	E_{max}	Highest entropy level detected across duration of selected call	Bits	Raven Pro
Call duration	t	Length of selected call	Seconds	Raven Pro
Number of harmonics	$N_{harmonics}$	Number of detectable harmonics at regular intervals of the observed F_0	Count	Manual
Number of inflections	$N_{inflections}$	Number of points where there is a sign change in the slope of F_0 across the duration of the selected call	Count	Manual
Start fundamental frequency	$F0_{start}$	F_0 observed at the start of the selected call	Hz	Manual
End fundamental frequency	$F0_{end}$	F_0 observed at the end of the selected call	Hz	Manual
Minimum fundamental frequency	$F0_{min}$	Lowest observed F_0	Hz	Manual
Maximum fundamental frequency	$F0_{max}$	Highest observed F_0	Hz	Manual
Delta fundamental frequency	ΔF_0	Change in F_0 from the start to the end of the selected call ($F0_{end}$–$F0_{start}$)	Hz	Manual (Derived)
Minimum fundamental frequency position	Min. F_0 Position	Relative position of lowest observed F_0 in call across the duration of the call (T_{min} (s)/Duration (s))	Proportion of Duration	Manual (Derived)
Maximum fundamental frequency position	Max. F_0 Position	Relative position of highest observed F_0 in call across the duration of the call (T_{max} (s)/Duration (s))	Proportion of Duration	Manual (Derived)
Fundamental frequency range	$F0_{range}$	Difference between maximum and minimum observed F_0 ($F0_{max}$–$F0_{min}$)	Hz	Manual (Derived)
Fundamental frequency fluctuation	$F0_{fluctuation}$	Difference between $F0_{range}$ and the absolute ΔF_0, representing the fluctuation of the fundamental frequency across the duration of the call ($F0_{range}$–$\lvert\Delta F_0\rvert$)	Hz	Manual (Derived)

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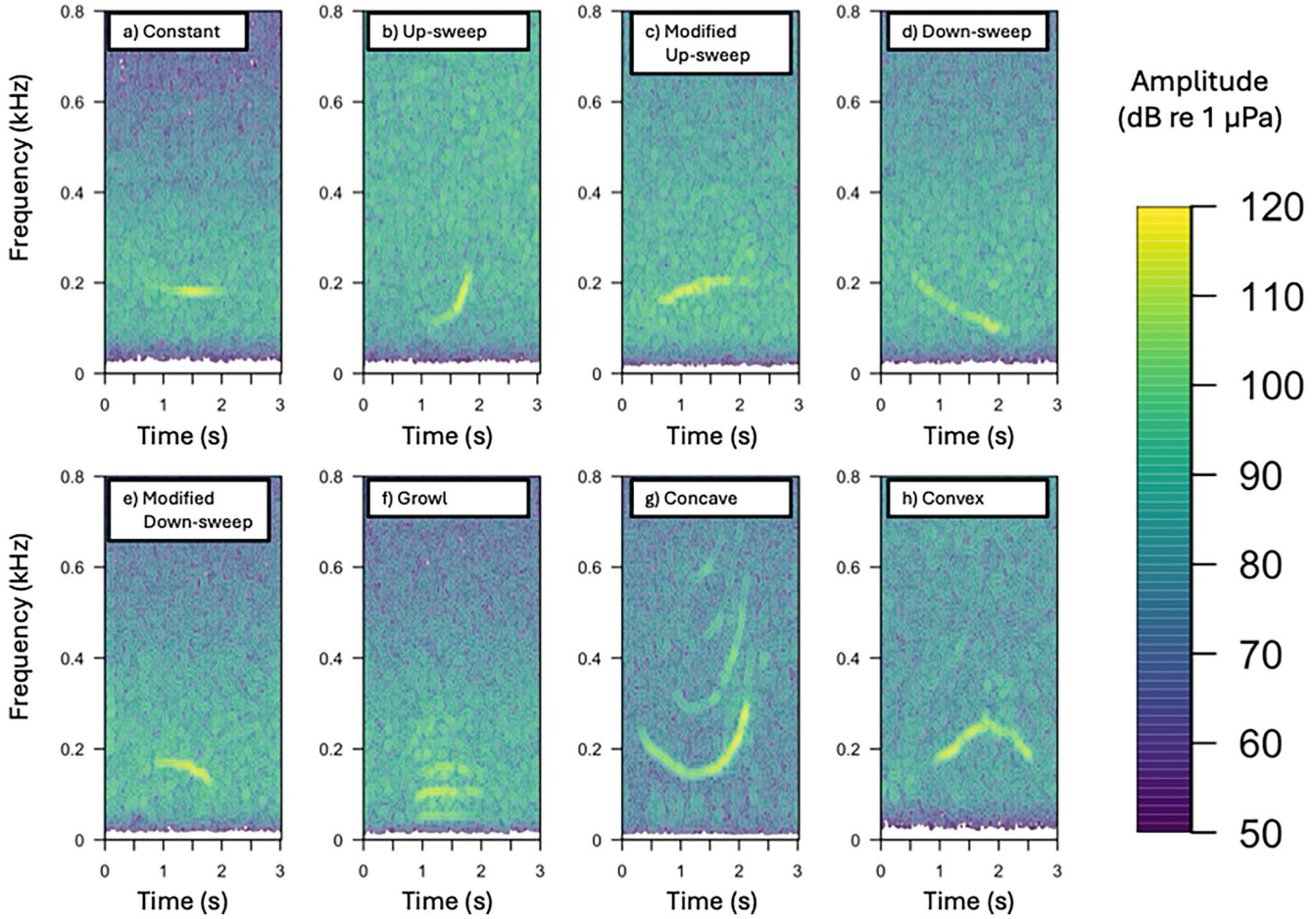

FIGURE 2 | Spectrograms highlighting the features of the final 8 bowhead whale (*Balaena mysticetus*) call types (a–h) classified. All spectrograms were computed using a 7000-point fast Fourier transform and 90% overlap.

bowhead whale calls divided into eight distinct categories (Figure 2).

2.3 | Statistical Analysis

All statistics were performed in R version 4.5.1 (R: A Language and Environment for Statistical Computing 2025) and data wrangling was done through the *tidyverse* package (Wickham et al. 2019). Results for all statistical tests were considered significant at a level of significance of $\alpha \leq 0.05$.

In order to accurately classify the different vocalizations of BCB bowhead whales, we used a random forest supervised machine learning classification model through the *randomForest* package (Breiman et al. 2022). Random forest models are robust to outliers, nonnormal, and nonindependent data (Breiman 2001). In brief, we split our data into training and testing datasets following an 80–20 split respectively through the *caret* package (Kuhn et al. 2019), resulting in a 1860 call training dataset and a 466 call testing dataset. Following the random split of training and testing data, a random forest model with 10,000 trees was built using the 16 acoustic features previously described, selecting four features at random for each node. This model was then validated against the testing dataset to determine overall balanced accuracy (as defined as the percentage of observations that were classified correctly), class-dependent specificity and accuracy for each call.

3 | Results

Of the eight distinct call categories identified, up-sweeps, down-sweeps, and constant calls made up over 53% of the 2326 calls used in our final analysis, with up-sweeps occurring most frequently (Figure 3). All call types were detected at all sites across all years, with the exception of modified down-sweep calls at Franklin Bay over the 2019–2020 season and growl calls at Sachs Harbour over the 2020–2021 season (Supplementary Table 1).

3.1 | Classification Model

Our random forest classification model was able to predict the true category of calls from our testing dataset with 86% accuracy (95% CI = 0.83, 0.89; No-information rate = 0.24; $p < 0.001$; Figure 4) and successfully converged for all 16 features included. Of the eight call categories tested, constant, up-sweep, down-sweep, growl, and concave were all classified with > 90% accuracy, while modified up-sweep, modified down-sweep, and convex calls were all classified with > 80% accuracy (Table 4). The mean ± standard error of the mean (SEM) of each acoustic

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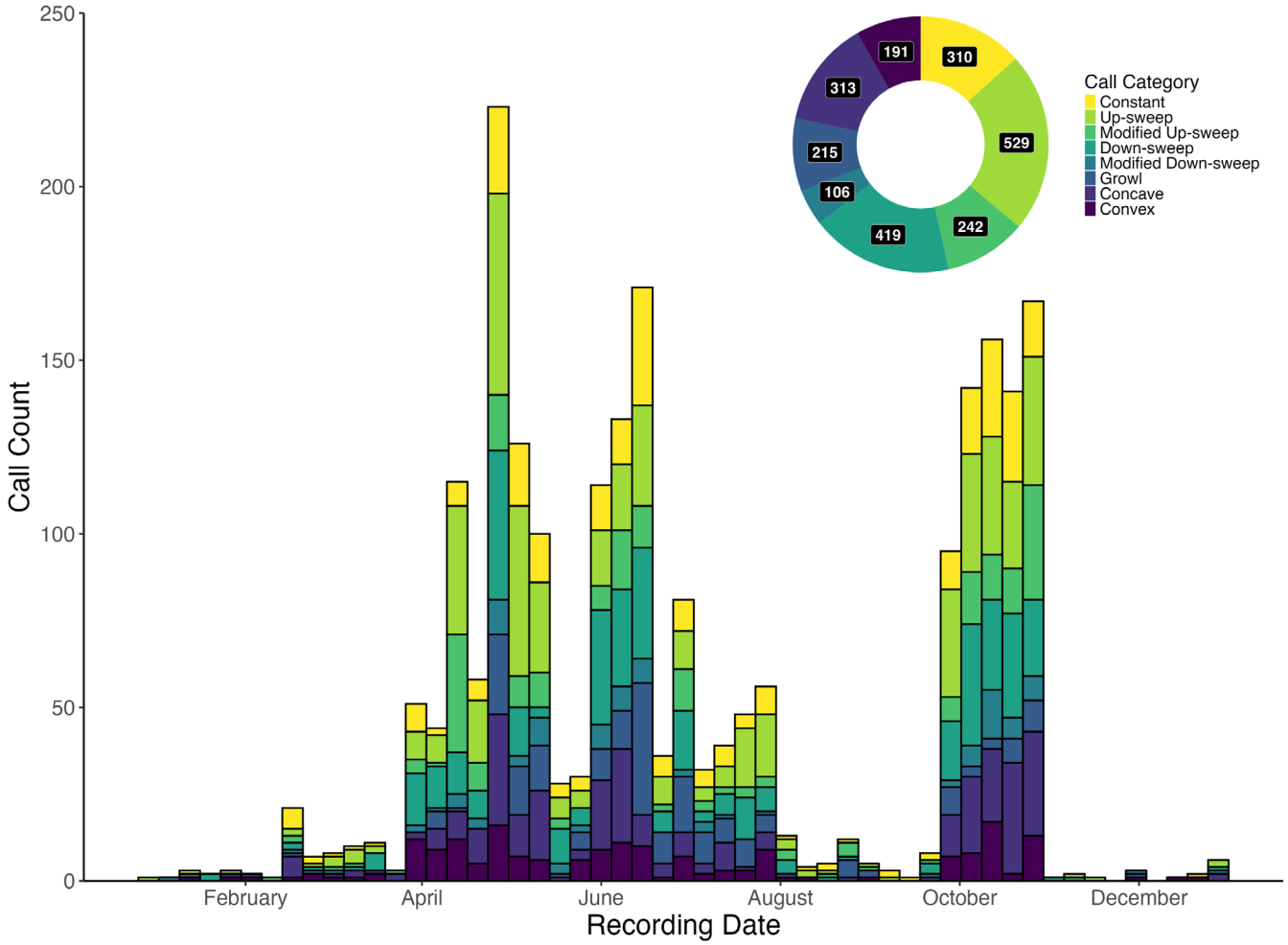

FIGURE 3 | Histogram of the distribution of all $n = 2326$ bowhead whale (*Balaena mysticetus*) calls grouped by call categories across recording dates within 1-week bins. The numbers on the inset donut-chart refer to the number of calls in each call category.

feature for all call types is summarized in Table 5. Among the 16 acoustic features included in our random forest model, six features strongly contributed to call classification with > 100 MDG (Table 5).

4 | Discussion

Among the calls produced, up-sweep, down-sweep, and constant calls were the most common vocalizations identified, representing 22.74%, 18.01%, and 13.37% of all calls included in this analysis respectively. Conversely, modified down-sweeps were the least observed calls in our dataset, representing only 4.56% of all calls. This distribution of calls is perhaps not surprising, as many of the distinctions made within our initial manual labeling represent subjective cut-offs in fundamental frequency characteristics that would otherwise constitute graded variation between up-sweeps and modified up-sweeps, down-sweeps and modified down-sweeps, and convex calls and both modified up-sweeps and modified down-sweeps (Fischer et al. 2017). These differences were largely related to the proportional change in F_0 relative to inflection points, with the modified up-sweeps and down-sweeps falling intermediate to respective up/down-sweeps and convex calls. This appears to be reflected in the relatively low balanced call accuracy for each of these three call categories.

Interestingly, all calls were present across almost all sites in each recording year, with the exception of modified down-sweeps at Franklin Bay in 2019–2020 and growls at Sachs Harbour in 2020–2021. This near ubiquitous presence of all eight call categories identified across all recordings suggests these calls may have a conserved function in either social communication or navigating the environment independent of seasonal activity (Seyfarth and Cheney 2003).

4.1 | Call Classification Model

Our classification model was able to reliably classify eight distinct BCB bowhead vocalizations with 86.05% accuracy. This level of model accuracy, combined with our observed class-specific accuracy of > 80% for all call categories examined, suggests our classification model performed well and is detecting meaningfully distinct vocalizations (Baumgartner and Mussoline 2011; Garland et al. 2015; Molder et al. 2024). Further, the call categories we have identified are largely aligned with those described in the existing literature (Clark and Johnson 1984; George et al. 1989; Ljungblad

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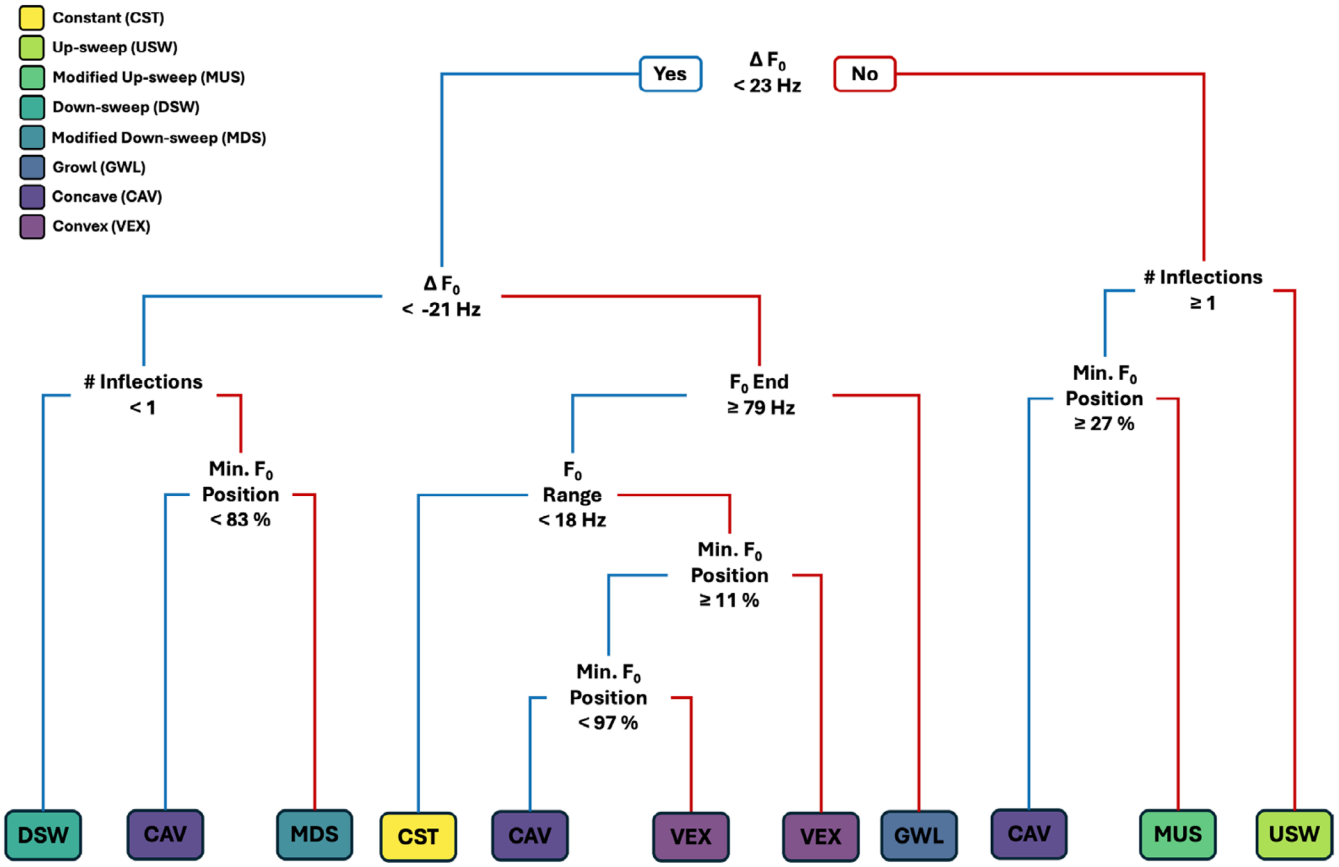

FIGURE 4 | Dendrogram of random forest averaged branching decisions, separating bowhead whale (*Balaena mysticetus*) calls into eight distinct call categories based on five acoustic features. Each node represents a grouping decision based on a feature threshold, with blue branches to the left representing agreement (Yes) and red branches to the right of each node representing disagreement (No) with the selected threshold. These cumulative averaged decisions are used to separate all eight call categories at the base of the tree.

TABLE 4 | Classification statistics for the eight call categories identified in our random forest classifier, including the sample size and the balanced percent accuracy for each call category.

Call category	Calls in testing dataset (*n*)	Random forest balanced accuracy
Constant	60	93.65%
Up-sweep	111	95.55%
Modified up-sweep	42	87.75%
Down-sweep	82	92.90%
Modified down-sweep	22	85.80%
Growl	51	93.15%
Concave	58	94.71%
Convex	40	80.78%

et al. 1982; Sawyer 2024). Specifically, our description of eight distinct call categories encompasses the variation within simple moans defined by Ljungblad et al. (1982), allowing for differentiation within this subclass of calling behavior. Further, our classifications of up sweeps, down sweeps, their modified counterparts, and both concave and constant calls is in line with those found by Sawyer (2024), while also identifying further variation in growls and convex calls. This represents a significant first step in establishing a comprehensive quantitative repertoire of BCB bowhead vocalizations, distinctly classifying the most common tonal calls produced by this population across multiple years.

The contour of the F_0 as measured via spectrogram was responsible for a large proportion of variation between call categories. Specifically, changes in F_0 across the duration of tonal calls disproportionately aided in classifying call categories, accurately separating down-sweeps from up-sweeps, as well as their associated modified counterparts. Further, in quantifying the position of the maximum and minimum F_0 within each call, as well as the number of inflection points, we were able to effectively describe the shape of each call, providing enough information for our random forest model to accurately classify each call type. Despite the success of our model in accurately classifying different call categories, the process of feature extraction was relatively labor intensive, involving multiple rounds of visual and aural review by analysts, and detailed manual annotation of multiple acoustic features for every call included. Given the importance of the F_0 contour in dictating call type, future methods to extract these features may instead choose to incorporate convolutional neural networks to extract F_0 contour elements (Gupta et al. 2020). The future incorporation of machine learning elements would significantly reduce the manual labor involved, allowing for higher throughput of call classification, and

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TABLE 5 | Mean decrease Gini (MDG), mean ± SEM, and range of observed values for all 16 acoustic features measured for each of the eight distinct bowhead whale (*Balaena mysticetus*) call categories identified.

Feature	MDG	Measurement	Constant	Up-sweep	Mod. up-sweep	Down-sweep	Mod. down-sweep	Growl	Concave	Convex
ΔF (Hz)	67.77	Mean ± SEM	77.57 ± 143.4	188.31 ± 419.23	163.81 ± 432.8	148.2 ± 236.73	208.01 ± 534.97	266.19 ± 274.05	203.43 ± 636.1	157.76 ± 339.19
		range	27.21–1827.76	37.74–4741.61	40.79–5665.69	37.38–3887.39	40.63–4669.41	64.67–2363.35	43.08–6831.36	39.42–3584.34
F_{peak} (Hz)	28.73	Mean ± SEM	160.51 ± 39.38	173.03 ± 64.07	190.08 ± 95.92	172.56 ± 81.92	194.24 ± 167.02	111.03 ± 51.05	180.8 ± 84.38	179.4 ± 73.3
		range	70.31–328.13	17.58–1001.95	87.89–1148.44	70.31–1312.5	70.31–1552.73	29.30–310.55	58.59–1236.33	41.02–750.00
E_{min} (bits)	46.67	Mean ± SEM	1.74 ± 0.37	2.41 ± 0.64	2.12 ± 0.55	2.28 ± 0.58	2.04 ± 0.59	2.96 ± 0.66	1.97 ± 0.47	2.08 ± 0.53
		range	1.22–4.70	1.47–4.63	1.46–5.51	1.46–4.73	1.45–5.71	1.64–5.22	1.45–5.23	1.48–4.73
E_{max} (bits)	53.56	Mean ± SEM	2.89 ± 0.69	3.91 ± 0.85	3.71 ± 0.81	3.79 ± 0.76	3.7 ± 1.01	4.57 ± 0.64	3.68 ± 0.97	3.61 ± 0.89
		range	1.82–7.49	2.36–8.40	2.25–7.94	2.35–7.35	2.08–7.74	3.08–7.33	2.16–8.49	2.17–7.71
T (s)	41.05	Mean ± SEM	1.16 ± 0.54	1.04 ± 0.44	1.38 ± 0.52	1.18 ± 0.54	1.29 ± 0.61	1.24 ± 0.45	1.5 ± 0.63	1.39 ± 0.67
		range	0.292–3.69	0.30–3.29	0.57–3.84	0.25–4.19	0.38–3.68	0.586–2.81	0.34–4.75	0.48–5.30
$N_{harmonics}$ (n)	27.89	Mean ± SEM	0.15 ± 0.59	0.19 ± 1.24	0.19 ± 0.93	0.11 ± 0.64	0.4 ± 1.21	2.9 ± 2.26	0.31 ± 1.57	0.3 ± 1.33
		range	0–6	0–14	0–9	0–8	0–8	0–17	0–20	0–14
$N_{inflections}$ (n)	**157.56**	Mean ± SEM	**0.8 ± 1.14**	**0.15 ± 0.56**	**1.42 ± 0.68**	**0.23 ± 0.54**	**1.53 ± 0.69**	**0.88 ± 0.62**	**1.55 ± 0.93**	**1.35 ± 0.69**
		range	0–7	0–9	1–5	0–3	1–4	0–3	0–6	0–5
$F0_{start}$ (Hz)	60.53	Mean ± SEM	157.75 ± 39.87	134 ± 59.47	144.87 ± 77.44	232.52 ± 108.64	205.35 ± 88.12	64.51 ± 24.09	199.09 ± 65.22	152.04 ± 65.46
		range	46.88–328.13	29.30–996.09	35.16–1066.41	58.59–1306.64	87.89–703.13	29.230–152.34	76.17–650.39	52.73–626.95
$F0_{end}$ (Hz)	65.06	Mean ± SEM	157.54 ± 39.26	226.24 ± 82.05	201.24 ± 82.36	144.29 ± 74.8	152.18 ± 65.22	62.27 ± 23.66	204.65 ± 96.61	162.68 ± 64.96
		range	46.88–316.41	70.31–1066.41	105.47–1189.45	29.3–1236.33	52.73–439.45	23.44–146.48	76.17–1441.41	46.88–585.94
$F0_{min}$ (Hz)	42.17	Mean ± SEM	152.14 ± 39.14	133.16 ± 59.12	143.18 ± 75.7	142.9 ± 74.55	147.65 ± 63.95	57.39 ± 23.03	155.23 ± 55.57	145.04 ± 61.77
		range	46.88–316.41	29.30–990.23	35.16–1037.11	29.3–1236.33	41.02–439.45	23.44–146.48	52.73–621.09	46.88–585.94
$F0_{max}$ (Hz)	69.32	Mean ± SEM	163.55 ± 39.9	226.36 ± 82.04	209.54 ± 82.87	232.77 ± 108.48	212.71 ± 87.57	76.5 ± 24.58	220.92 ± 95.77	198.24 ± 77.57
		range	52.73–328.13	70.31–1066.41	117.19–1189.45	58.59–1306.64	93.75–720.7	29.230–169.92	117.19–1441.41	82.03–750.00
Minimum F_0 Position (%)	**175.02**	Mean ± SEM	**0.51 ± 0.44**	**0.02 ± 0.08**	**0.03 ± 0.09**	**0.96 ± 0.13**	**0.91 ± 0.17**	**0.53 ± 0.47**	**0.49 ± 0.2**	**0.31 ± 0.44**
		range	0–1	0–0.5	0–0.46	0–1	0–1	0–1	0–1	0–1

(Continues)

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TABLE 5 | (Continued)

Feature	MDG	Measurement	Constant	Up-sweep	Mod. up-sweep	Down-sweep	Mod. down-sweep	Growl	Concave	Convex
Maximum F_0 Pos (%)	**195.89**	Mean ± SEM	**0.45 ± 0.44**	**1 ± 0.01**	**0.8 ± 0.16**	**0 ± 0.05**	**0.14 ± 0.16**	**0.44 ± 0.32**	**0.5 ± 0.48**	**0.56 ± 0.19**
		range	0–1	0.88–1	0.27–1.00	0–1	0–1	0–1	0–1	0–1
ΔF_0 (Hz)	**258.11**	Mean ± SEM	**−0.21 ± 9.8**	**92.24 ± 64.33**	**56.38 ± 34.3**	**−88.23 ± 69.16**	**−53.18 ± 53.86**	**−2.23 ± 13.74**	**5.56 ± 63.76**	**10.65 ± 36.94**
		range	−52.74–35.16	5.86–685.55	−5.86–205.08	−574.22–82.03	−351.56–111.33	−46.875–41.02	−199.22–791.02	−105.47–328.13
$F0_{range}$ (Hz)	**151.69**	Mean ± SEM	**11.42 ± 7.19**	**93.2 ± 64.3**	**66.36 ± 35.48**	**89.86 ± 69.16**	**65.06 ± 53.45**	**19.1 ± 12.3**	**65.69 ± 63.41**	**53.19 ± 47.24**
		range	0–52.74	11.72–685.55	17.58–222.66	5.86–591.8	11.72–375	0–87.89	11.72–820.31	11.72–533.20
$F0_{fluctuation}$ (Hz)	**141.96**	Mean ± SEM	**4.14 ± 5.66**	**0.95 ± 3.53**	**9.93 ± 8.45**	**1.24 ± 4.01**	**9.78 ± 9.96**	**9.13 ± 8.73**	**30.1 ± 28.16**	**30.46 ± 25.96**
		range	0–23.44	0–29.30	0–41.02	0–35.16	0–52.74	0–52.74	0–257.81	0–205.08

Note: Acoustic features with an MDG ≥ 100 are displayed in bold to indicate features that significantly improve model accuracy.

ultimately allowing more relevant ecological questions to be addressed using larger datasets collected across larger time scales.

While our current model performed well at identifying eight distinct call categories, this still falls short of a complete bowhead vocal repertoire. Bowhead whales are capable of producing highly complex vocalizations, such as biphonic calls produced with both tonal and pulsed components (Stafford and Clark 2021) and have incredible variation in song structure (Blackwell et al. 2007; Stafford et al. 2018; Thomisch et al. 2022). Despite this emergent complexity, the units of each phrase within songs have largely similar tonal structures to those of the calls we have identified here (Delarue et al. 2009; Thomisch et al. 2022). Further, building on our existing classification system for tonal features, future models should aim to describe higher frequency formants such as pulsed components, building a more complete acoustic repertoire for comparison between populations and across migratory patterns.

Finally, our classification model has the potential to be utilized in future studies investigating the functional roles of different calls. While it is tempting to hypothesize as to the functional role of certain calls, such as the highly stereotyped and low frequency growl calls playing a role in mediating agonistic interactions by providing honest information regarding size and competitive ability (Wells 1978), our current study does not allow for this level of resolution. Instead, we suggest that applying our methods for acoustic feature extraction and our classification model to audio data collected via individual animal-mounted biologgers, such as CATS tags (Cade et al. 2021), would allow for specific diving and feeding behaviors to be correlated to distinct call categories and facilitate attributing them function (Fortune et al. 2020; Molder et al. 2024). Further, conspecific social interactions may be inferred by differentiating sender and receivers through the distinct accelerometric signals from calling focal individuals (Goldbogen et al. 2014). This would provide novel data on the likelihood of individuals to produce specific calls in response to conspecific signals, elucidating the social function of different call categories.

To our knowledge, this is the first peer-reviewed quantitative classification model for the tonal calls of BCB bowhead whales. Along with the descriptive statistics provided for each relevant call feature, our results can be used to standardize future repertoire analyses and dialect comparisons between the BCB population and other bowhead populations across the Arctic.

Author Contributions

Alexander J. Hare: funding acquisition, writing – original draft, conceptualization, methodology, validation, visualization, writing – review and editing, formal analysis, resources, data curation. **William D. Halliday:** conceptualization, investigation, funding acquisition, methodology, writing – review and editing, project administration, data curation, supervision, resources, software. **Nikoletta Diogou:** methodology, writing – review and editing, validation, formal analysis, data curation. **Stan E. Dosso:** investigation, funding acquisition, writing – review and editing, project administration, supervision, resources, conceptualization. **Bridgette Nzomwita:** formal analysis, writing – review and editing. **Humfrey Melling:** writing – review and editing, funding acquisition, resources.

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Andrea Niemi: writing – review and editing, resources. **Xavier Mouy:** methodology, software, writing – review and editing. **Stephen J. Insley:** conceptualization, investigation, funding acquisition, writing – review and editing, project administration, supervision, resources.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Supplementary Table 1:** Number of medium or higher quality bowhead whale (*Balaena mysticetus*) calls obtained from each call category at eight recording stations across three seasons. **Supplemental Figure 1:** Histogram demonstrating the distribution of all 2326 bowhead whale (*Balaena mysticetus*) call SNRs.

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