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ARTICLE

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Using acoustic monitoring to reveal nearly year-round presence of humpback whales (*Megaptera novaeangliae*) in the waters of southern Iceland

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Abstract

Icelandic waters are a crucial feeding ground for North Atlantic humpback whales, yet their occurrence in these subarctic waters remains underexplored. This study examined seasonal and diel patterns in humpback whale occurrence off the Vestmannaeyjar archipelago, southern Iceland, from June 2018 to May 2019, using automated acoustic detections from bottom-moored hydrophones. Vocalizations were manually categorized into social calls, song fragments, or songs. Further classification identified seven social sound types and 25 unique song units. Humpback whales were detected on 126 out of 329 recording days and were present in nearly all months except April and May. Social calls were most common in summer and fall, while song fragments and songs were prevalent in winter. No diel singing pattern was observed. These findings suggest southern Iceland serves as a vital habitat for humpback whales, acting as a feeding ground in summer and a migration stopover or overwintering site in winter. The study underscores the potential of acoustic monitoring to uncover important habitats year-round, especially when field observations are scarce, and emphasizes the need for ongoing monitoring of habitat use. Continued acoustic monitoring could provide further insights into the whales' behavioral patterns and preferences, essential for their conservation.

KEYWORDS

automated detector, diel behavior, North Atlantic, PAM, social calls, songs

1 | INTRODUCTION

Humpback whales (*Megaptera novaeangliae)* have a worldwide distribution and are known for undertaking long-distance annual migrations from their feeding grounds, in temperate and polar waters, where they occur mainly during summer, to their breeding grounds in tropical waters, presumably for mating and calving, during winter (Dawbin, 1966; Katona & Berard, 1990; Rasmussen et al., 2007). In the North Atlantic, humpback whales mainly feed in the Gulf of Maine in the USA, eastern Canada (including the Gulf of St. Lawrence, Labrador, Newfoundland, and Baffin Island), Greenland, Iceland, and Norway (Clapham ~~et al.~~, 2000). The major known breeding grounds are in the West Indies (Kettemer et al., 2022; Stevick et al., 1998). However, a smaller proportion of Northeast Atlantic humpback whales migrates to a breeding ground near Cape Verde (Stevick et al., 2006; Wenzel et al., 2020).

In Icelandic coastal waters, humpback whales are commonly sighted across the southwest, west, and north, where whale watching activity is well developed (Rasmussen, 2014). Since the first systematic cetacean survey in Iceland in 1987, humpback whale occurrence has increased, likely reflecting population recovery following the commercial whaling moratorium (Pike et al., 2020; Víkingsson et al., 2015). In the southern and eastern coastal waters of Iceland, humpback whale occurrence and seasonality are understudied, although these areas may be a part of the feeding grounds or important stopovers for whales on their migration to and from breeding grounds (Kettemer et al., 2022). While the importance of Iceland as a feeding ground to humpback whales is well known, winter occurrence has also been reported, particularly in the north, where singing activity is detected in the wintertime (Magnúsdóttir & Lim, 2019; Magnúsdóttir et al., 2014).

The use of feeding grounds well into winter has also been observed in North Atlantic feeding grounds outside of Iceland. For example, humpback whale aggregations have been observed feeding on herring (*Clupea harengus*) in the fjords of northern Norway between November and February (Jourdain & Vongraven, 2017). Similarly, capelin (*Mallotus villosus*) appears to be one of the targeted prey in subarctic areas during winter months, with humpback whales observed following its migration (Gunnlaugson & Víkingsson, 2014; Magnúsdóttir, 2007; Víkingsson, 2004). Nevertheless, individuals that were satellite tagged in Norway in winter still migrated to the breeding grounds during the same year (Kettemer et al., 2022). In addition, there is evidence that migrating whales can use multiple feeding grounds and respond to foraging opportunities during their route southbound (Kettemer et al., 2022, 2023). The consequent reduction of their time in breeding grounds may be a strategy to maximize energy intake (Magnúsdóttir & Lim, 2019).

Increased year-round monitoring throughout the North Atlantic would result in a better understanding of the movements, abundance, and behavior of humpback whales and the importance of different areas for feeding and migration to and from breeding grounds.

The Vestmannaeyjar archipelago, in the south of Iceland, is a spawning ground for herring in July (Jakobsson & Stefánsson, 1999) and for capelin between February and March (Vilhjálmsson, 2002). The periodic abundance of schooling fish is key to the high marine biodiversity of the archipelago and attracts many marine mammal predators. Opportunistic shore-based observations of humpback whales in summer and winter, as well as a satellite-tagged humpback whale travelling through the area during its migration to breeding grounds (Kettemer et al., 2022, 2023), suggested that Vestmannaeyjar may be an important area for humpback whales in different seasons. However, the information on cetacean occurrence from this area is sparse due to little year-round monitoring and no whale-watching activities. Visual data collection on cetaceans can be very challenging because weather conditions often limit research effort. Hence, passive acoustic monitoring (PAM), i.e., using sound recorders to monitor soniferous wildlife and their acoustic environment, can be a more effective approach to study the presence of acoustically active marine mammal species such as humpback whales (Mellinger et al., 2007; Van Parijs et al., 2009).

Humpback whales produce a variety of sounds, from simple social calls to complex songs (Au et al., 2006; Cerchio & Dalheim, 2000; Dunlop et al., 2007; Payne & McVay, 1971). Social calls are short calls made by individuals of both sexes and all age classes that do not seem to follow specific patterns. These calls can be heard year-round and mainly on foraging grounds (Epp et al., 2021; Fournet et al., 2015; Stimpert et al., 2011; Thompson et al., 1977), but also in the breeding grounds and during migration (Dunlop et al., 2008; Rekdahl et al., 2017; Silber, 1986). They are usually related to a social context (e.g., competitive aggressive behavior between males: Dunlop et al., 2008; Silber, 1986; by female-calf pairs to maintain contact: Dunlop et al., 2007; Zoidis et al., 2008). Social calls are commonly classified into low-frequency, pulsed, and high-frequency sounds (Dunlop et al., 2008; Epp et al., 2021).

Songs can be heard mostly in the breeding grounds and are presumably only produced by males, suggesting a possible role in mating and/or male–male interactions (Cholewiak, 2008; Darling et al., 2006; Darling & Bérubé 2001; Darling & Sousa-Lima 2005; Herman, 2017; Smith et al., 2008; Tyack, 1981). The seasonal onset of humpback whale song is not yet fully understood; however, it is known that in the boreal fall humpback whales primarily produce "song fragments" (Kowarski et al., 2019, 2021). These are vocalizations arranged like a song but that are incomplete or inconsistent, such as song units being repeated without a clear phrase structure (Mattila et al., 1987; Vu et al., 2012). Humpback whale vocalizations show a gradual progression from only social calls to song fragments and finally to full songs (Kowarski et al., 2022).

A song is composed of a complex series of repetitive and stereotyped sounds that are displayed in a hierarchical structure (Cholewiak et al., 2013; Payne & McVay, 1971). Humpback whales can sing for up to 22 hr (Winn & Winn, 1978), producing "song sessions" made up of repeated "units" that form "phrases," which create "themes" that make up the "song" or "song cycle" (Payne & McVay, 1971). Singing activity often peaks during the nighttime in breeding grounds, possibly because individuals balance different strategies at different times of the day: singing during the dark hours and competitive behaviors that rely on visual cues during the daytime (Au et al., 2000). Humpback whale songs are also known to have a cultural component (Garland et al., 2011, 2022; Noad et al., 2000): different humpback whale populations can display different song compositions, but all individuals within a breeding population sing the same song (Darling et al., 2019; Garland et al., 2013; Murray et al., 2012). Increasing evidence indicates that singing activity also occurs in feeding grounds (e.g., Baker et al., 1985; Charif et al., 2001; Clark & Clapham, 2004; Gridley et al., 2018; Magnúsdóttir et al., 2014; McSweeney et al., 1989; Stimpert et al., 2012; Tyarks et al., 2021; Van Opzeeland et al., 2013; Vu et al., 2012).

Humpback whales produce sound year-round, making PAM a suitable tool to investigate the occurrence of humpback whales in remote areas with harsh weather conditions, such as the subarctic waters of south Iceland. In this study, we used a bottom-moored autonomous recorder to assess the importance of the Vestmannaeyjar archipelago in south Iceland for humpback whales by (1) investigating seasonal and diel variations in the vocal behavior of humpback whales in the area and (2) providing a detailed description of the social calls and song units that were recorded.

2 | MATERIALS AND METHODS

2.1 | Data collection

Acoustic data were collected with an autonomous recorder (SoundTrap 300 HF; Ocean Instruments Inc., Auckland, NZ) deployed in the Vestmannaeyjar archipelago, Iceland (Figure 1; 63°21.690′N 20°27.360′W). The recorder was part of a small subsurface mooring with an acoustic release system (Lightweight Release Transponder; Sonardyne, Yateley, UK). The hydrophone and recording chain had a combined sensitivity of −172.4 dB re 1 μPa^{-1} and a flat (±3 dB) response at frequencies up to 150 kHz. Two deployments were conducted at the study site: the first, labeled "Summer," from June 11 to August 17, 2018 (66 days) and the second, labeled "Winter," from August 22, 2018 to May 10, 2019 (261 days). The hydrophone depth was between ~85 and 90 m. The Summer deployment was a continuous recording at 96 kHz sampling rate, providing audio files with a duration of 3 hr each. Winter had a sampling rate of 48 kHz and a duty cycle of 16.7%, recording a 2.5 min audio file every 15 min.

2.2 | Data analysis

To identify humpback whale sounds in the acoustic recordings, an automated detector and classifier developed by JASCO Applied Science (Canada) and Fisheries and Oceans Canada (Moloney et al., 2014; Mouy et al., 2015) was used. The output of the humpback whale detector/classifier included a confidence value between 0% and 100% for each detection. Therefore, a "confidence threshold" was applied so that the filtered output only included detections

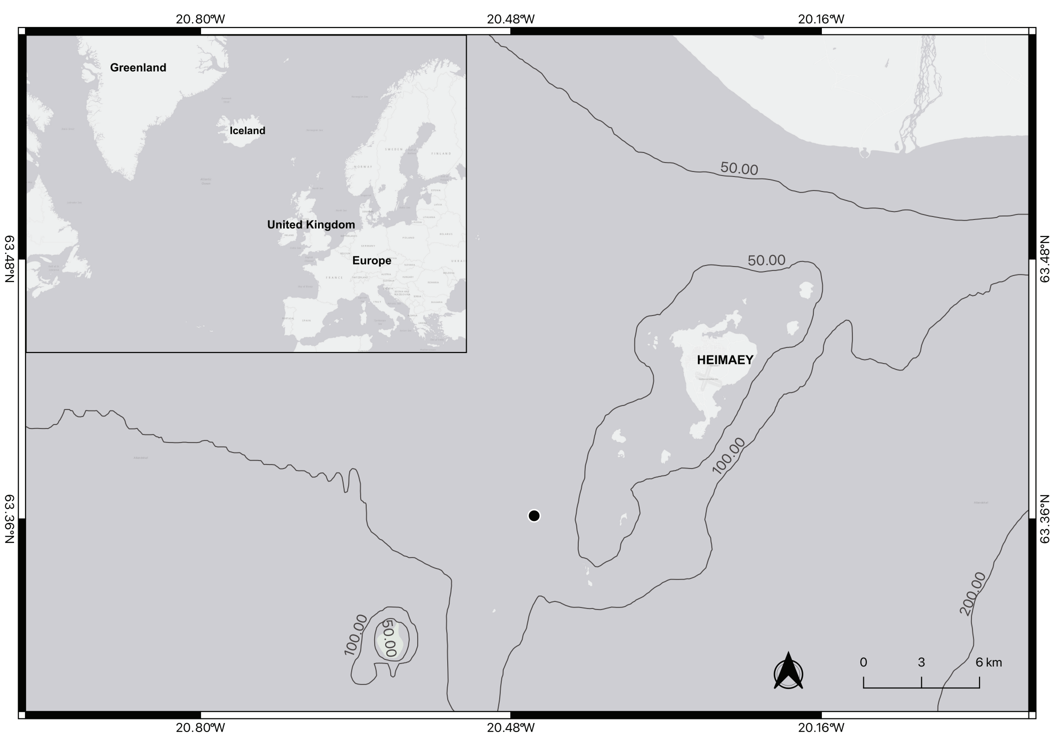

FIGURE 1 Map of the study area, showing the Vestmannaeyjar archipelago in the south of Iceland. The hydrophone location is indicated with the black circle. The map was created in QGIS using the coordinate reference system WGS 84, EPSG: 4326, and a world (source: ENRSI) and bathymetry map (source: EMODnet).

above the chosen threshold. The threshold settings are discussed further below. Each automated detection was visualized using spectrograms and manually confirmed by a human auditor in the software Raven Pro (Cornell Lab of Ornithology, 2022). The spectrograms were generated using the following settings for Summer: Hann window, NFFT 32,768, 2.93 Hz resolution, and 50% overlap and Winter: Hann window, NFFT 8,192, 5.86 Hz resolution, and 50% overlap.

2.2.1 | Detector ground-truthing and settings

We evaluated the performance of the automatic detector/classifier for the Summer deployment. The performance was evaluated by (1) subsampling 15% of the total number of acoustic files, (2) manually annotating all humpback whale sounds in this subset, (3) running the humpback whale detector, and (4) comparing the manual annotations with the automatic detections. The confidence threshold was initially set at a relatively low value of 40% and all detections above this threshold were analyzed to investigate the effect of different threshold values on detector performance. This specific threshold was chosen as the minimum confidence value to consider based on time constraints and previous experiences with detecting humpback whales in the Pacific (e.g., Moloney et al., 2014). Our detector evaluation showed that even with the confidence threshold at 100%, a relatively high number of false positive detections was retained. False positives consisted of, for example, boat noise or low frequency sounds produced by killer whales (*Orcinus orca*; Samarra et al., 2016), which are abundant in the area in summer (Samarra et al., 2017). All true positive detections had a confidence value higher than 95%; therefore, the confidence threshold for the whole Summer deployment was set at 95%. For the Winter deployment, it was set to 80% because lower vessel activity and decreased killer whale presence led to fewer false positives. Nevertheless, because the performance of the detector/classifier was not quantified for the Winter deployment, all acoustic files with detections above the 80% threshold were manually checked to ensure no humpback whale sounds were missed. This approach increased the probability of capturing the humpback whale song and song fragments during that period.

2.2.2 | Seasonal and diel patterns in vocal behavior

A "presence day" was defined as a recording day that had at least one acoustic detection of a humpback whale that was confirmed by the auditor with high confidence, i.e., a sound with a frequency contour that was clearly visible in the spectrogram (the sound quality classification is discussed further below) and corresponded to a signal type described in the published literature. In cases of doubt, detections were evaluated by a second experienced auditor. The presence day approach was chosen as social calls were generally detected at lower rates than song units. We also calculated the daily number of detections of social calls and daily percentage of 2.5-min audio files with singing activity, to provide a more detailed view of the occurrence of humpback whale vocalizations.

Possible diel patterns in humpback whale vocal activity were investigated. Due to a small sample size for high-quality social calls, we did not investigate diel variations in social call production. Only the time that was determined to have singing activity (in the duty-cycled Winter deployment) was examined; song fragments were not included in this analysis. Each 15-min time bin was assigned a presence or absence of humpback whale song based on whether its corresponding 2.5 min file contained song units. We then divided the number of 15-min time bins by four to approximate the number of hours with singing activity for each day and light condition (light, dark, nautical twilight). This data set was normalized by dividing the number of hours containing singing activity per day by the number of hours within each light condition, to account for the change in light conditions throughout the study period. To determine the duration of each light condition per day, the altitude of the sun, obtained from the data archive of the United States Naval Observatory Astronomical Applications Department (retrieved from https://aa.usno.navy.mil) at the study site was used (Magnúsdóttir et al., 2014; Stafford et al., 2005). To test for a statistical difference in singing activity between the different light conditions, a nonparametric statistical test (Kruskal-Wallis) was carried out using R (R Core Team, 2021).

2.2.3 | Classification of humpback whale sounds

Analyses to manually classify humpback whale sounds were performed in Raven Pro and involved listening as well as visual inspection using spectrograms. Humpback whale sounds were first quality-scored on a scale of 0 (low) to 3 (high) based on a set of qualitative criteria related to the signal-to-noise ratio of the sound, as perceived by the auditor (scale adapted from Selbmann et al., 2021); quality 0: frequency contour is barely visible in the spectrogram and the sound is only faintly audible; quality 1: frequency contour is visible in the spectrogram but the start and end are not clear, harmonics not visible, and other sounds may overlap; quality 2: frequency contour is clear, including start and end, and some harmonics are visible; quality 3: frequency contour and start and end frequency of the sound are very clear, harmonics are also clearly visible. Only sounds of qualities 2 and 3 were used for further analyses.

Humpback whale vocalizations were initially categorized into social (nonsong) calls, song fragments, and song. Social calls were further classified to type (e.g., wops, rumbles, moans, growls, droplets; Table 1) following published catalogs (Dunlop et al., 2008; Epp et al., 2021; see Table 1 for details). Only a basic description of social calls was deemed possible due to relatively low numbers of high-quality sounds (i.e., qualities 2 and 3).

Song fragments were defined as sequences of sounds displaying, but incompletely, the typical patterns of songs (i.e., units repeated to form a phrase). Song fragments represented periods in which singing activity was not consistent in time, e.g., phrases were not repeated to form a clear structure, and phrases were also mixed with typical social calls observed in the previous months (Kowarski et al., 2021; McSweeney et al., 1989).

Due to the duty cycle of the Winter deployment, it was impossible to record a whole song theme and not always possible to record a whole song phrase. For this reason, we only focused on describing the different unit types of

TABLE 1 Summary of the three categories of social calls identified by previous studies (Dunlop et al., 2008; Epp et al., 2021).

Category	Call types	Frequencies	Duration
Low frequency calls	wops growls rumbles low moans doos groans	>100 Hz	0.2–2.5 s
Pulsed calls	droplets honks swops tepees yips fluctuating moan	200 Hz–800 Hz	0.2–0.4 s
High frequency calls	oops cries squeaks yawps	>700 Hz	variable

the songs. To identify and characterize different unit types, the audio files containing singing activity were first viewed as spectrograms (Hann window, 4,096 discrete Fourier transform, 11.7 Hz resolution, and 50% overlap). Then, units were manually classified based on their aural and time-frequency characteristics. Each unit type was assigned a unique alphanumeric code following Tyarks et al. (2022) and similar units were classified with the same number but different letters, e.g., "2-satr" and "2a-sahtr" stand for "short ascending trill" and "short ascending high trill," respectively.

Acoustic parameters were extracted and measured from the fundamental frequency contour of the song units, following Warrant et al. (2020). The parameters measured were the duration, maximum, minimum, start and end frequency, bandwidth (maximum frequency − minimum frequency), frequency trend ratio (start frequency/end frequency), frequency range ratio (high frequency/low frequency), and number of inflections (Dunlop et al., 2007; Garland et al., 2017). The frequency and duration parameters for each unit were manually extracted by clicking on the spectrogram in Raven Pro. To test the agreement with the qualitative classification, the acoustic parameters were used as predictors in a random forest analysis performed in R (package "randomForest," number of trees = 1,000; Liaw & Wiener, 2002). The error rate for single unit types and for the overall classification were used to assess the robustness of the classification; the lower the error rate, the more robust the classification (Warrant et al., 2020). Diagnostics for the random forest analysis were also performed (see Figure S2).

3 | RESULTS

The two analyzed hydrophone deployments spanned a period of 329 days between June 2018 and May 2019 and had recording durations of 1,539 hr (Summer: 531 files of 3 hr each) and 1,045 hr (Winter: 25,090 files of 2.5 min each). Humpback whale acoustic presence was confirmed by the auditors for 129 (39%) of these recording days (Figure 2), with a total of 64,355 confirmed humpback whale sounds.

3.1 | Seasonal and diel variation in vocal behavior

During the Summer deployment, humpback whales were detected on 11 (16%) of 68 recording days, while during the Winter deployment, humpback whales were detected on 118 (45%) of 261 recording days. A marked increase in the presence of humpback whale sounds occurred between October, with 19% of days with detections, and November, with 70% of days with detections (Table 2). No humpback whale vocalizations were recorded during April and the beginning of May (Figure 2; end of deployment: May 10).

Whether social calls, song fragments, or songs were the most common category of humpback whale sounds strongly varied throughout the year (Figure 2). Between June and October, only social calls were detected (Figure 3a). In contrast, no social calls were identified between December and March, except on March 4 and 6 (Figure 3a). Song fragments, with a clear repetition of a rhythmic structure, were first detected November 11 (Figure 3b). In the beginning of November, both song-fragments and social calls were detected, while at the end of this month singing had become the dominant type of vocalization (Figure 2). Singing continued in December to March, the latter month having the highest numbers of acoustic detections per day and several days with singing in all audio files (Figure 3b). Songs were recorded in 74%, 86%, and 90% of the recording days during the months of January, February, and March, respectively (Table 2).

The daily percentages of 2.5-min audio files with song strongly varied between November 22 and March 30 (Figure 3b); however, light condition did not appear to affect humpback whale singing activity (Kruskal-Wallis test: $\chi^2 = 2.46$, $df = 2$, $p = .29$; Figure 4). The total number of 2.5-min audio files with singing activity were 1,342 for the dark, 422 for the twilight and 1,214 for the light period.

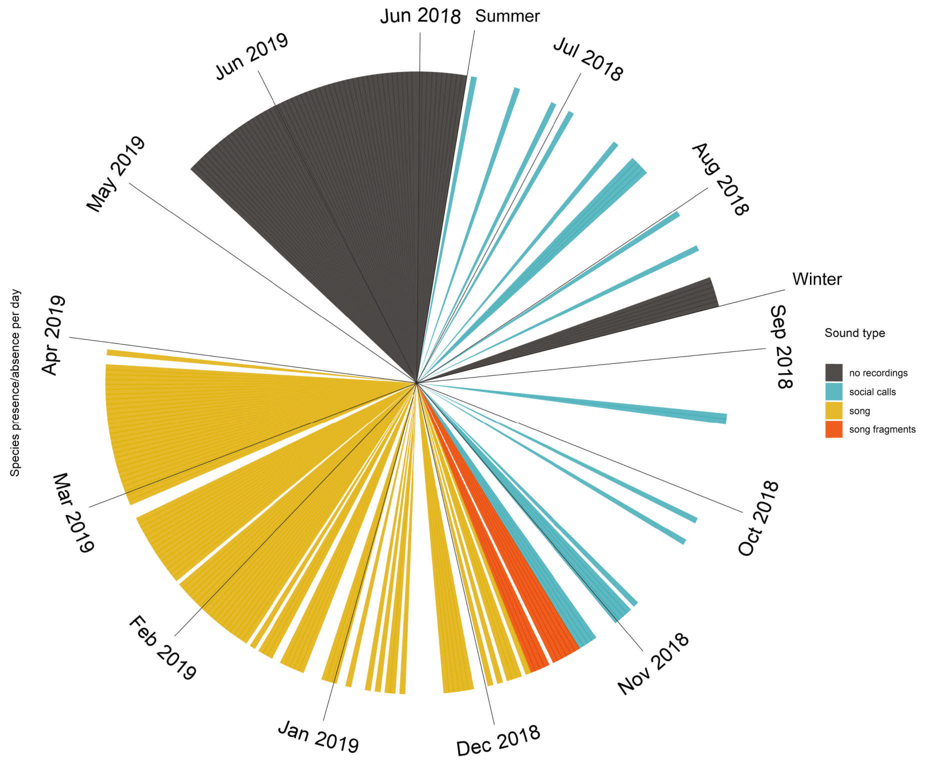

FIGURE 2 Seasonal occurrence of humpback whales based on acoustic recordings collected in the Vestmannaeyjar archipelago in the south of Iceland. The graph represents presence (colored fields) and absence (white fields) days over the study period. The start of the Summer and Winter deployments is indicated. Gray: periods without recording effort; blue: periods with predominantly social sounds, orange: periods with predominantly song-fragments, and yellow: periods with predominantly songs.

3.2 | Detailed description of social calls and song units

A total of 43 individual social calls were identified in the Summer deployment. All were considered low frequency calls since their minimum frequency was near or below 100 Hz. The call types low moans ($n = 18$), growls ($n = 8$), rumbles ($n = 6$), and wops ($n = 5$) were identified most regularly. For the Winter deployment, a total of 126 humpback whale calls were categorized as social calls, 60 of which were considered high enough quality (score 2 or higher) to be included in the detailed classification. Low-frequency pulsed, and high frequency call types were identified. Wops ($n = 23$), growls ($n = 17$) and rumbles ($n = 20$) were the most abundant call types in the recordings followed by low moans ($n = 7$). In addition, other types of pulsed calls such as honks, swops, and droplets were occasionally found. For spectrograms of example social calls see Figure S1.

The random forest analysis performed on the measurements of 988 song units confirmed the manual classification of song units with a consistency of 95.4% and an out-of-bag error estimate of 5.0%. Manual classification identified 25 song unit types in the audio recordings containing humpback whale song (see Figure 5 for examples of the most common song units). The list of unit types and their codes and the random forest matrix are presented in the Supplementary material (Tables S1 and S2).

TABLE 2 Acoustic occurrence of humpback whales in the study area, summarized by month.

Month (2018–2019)	No. of presence days/no. of recording days	Percentage of presence days	Type of sounds recorded
June	6/20	30%	social calls
July	6/31	19%	social calls
August	2/25	8%	social calls
September	2/30	7%	social calls
October	6/31	19%	social calls
November	21/30	70%	social calls, song fragments, song
December	12/31	38%	song
January	23/31	74%	song
February	24/28	86%	song
March	28/31	90%	song, social calls
April	0/30	0%	—
May	0/10	0%	—

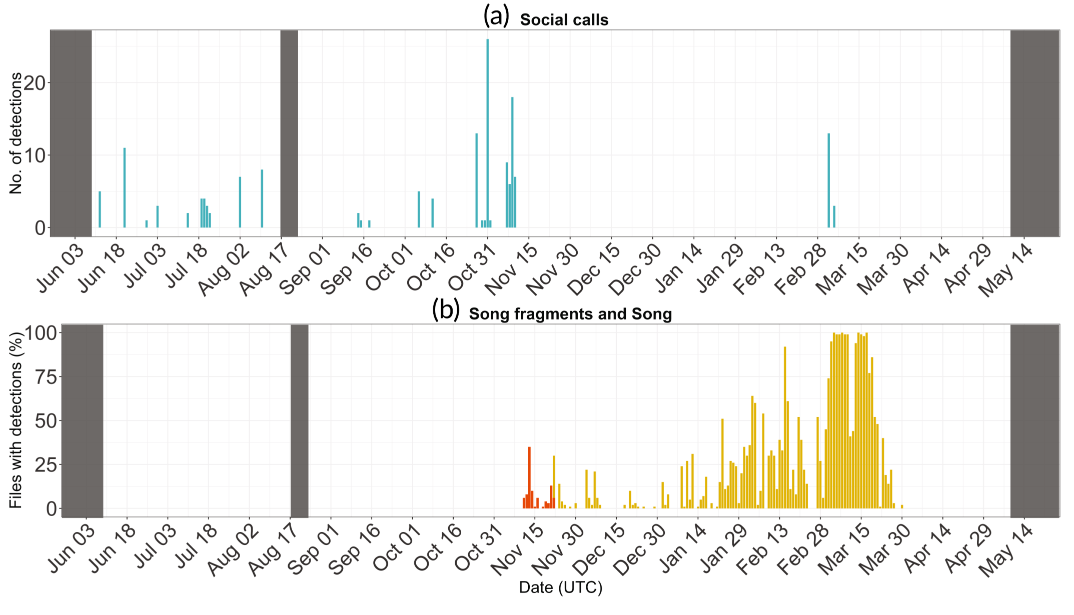

FIGURE 3 (a) Daily number of detections of social calls; (b) Daily percentage of audio files with song fragments (in orange) and song (in yellow) detections. Note that the recording effort varied from continuous for the Summer deployment (June 11 to August 17, 2018) to one 2.5-min audio file every 15 min (duty cycle: 17%) for the Winter deployment (August 22, 2018 to May 10, 2019), so the number of social calls received by the hydrophone during the Winter deployment was likely higher. Note also that the y-axes have different scales. Gray fields indicate no available recordings due to hydrophone maintenance.

4 | DISCUSSION

This study provides the first investigation of the seasonality and diel patterns of humpback whale acoustic occurrence, and description of social calls and song units, for the south of Iceland. Moreover, it contributes to a growing

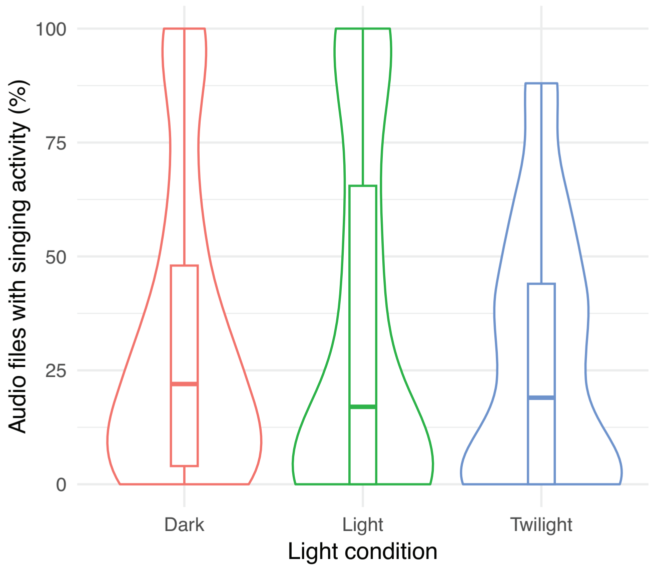

FIGURE 4 Comparison of the daily percentage of audio files containing humpback whale song across light conditions, based on the period when singing activity was observed (November 22, 2018 to March 30, 2019). One 2.5-min audio file was recorded every 15 min during this period, resulting in 96 files per day. Violin plots show the shape of the distributions; boxplots indicate their 25, 50, and 75 percentiles.

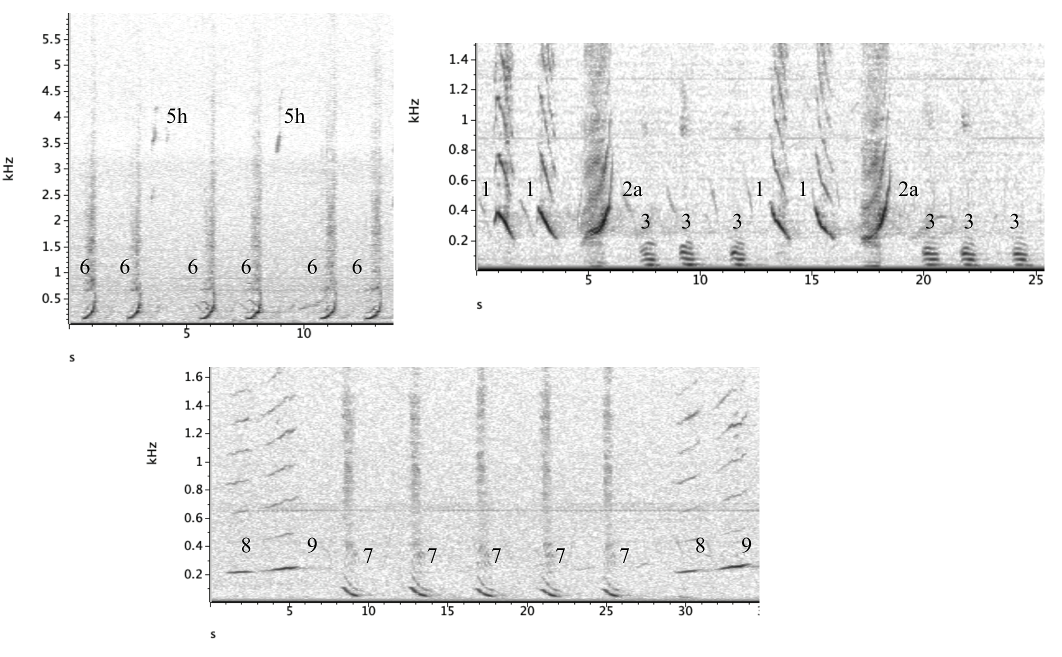

FIGURE 5 Example spectrograms of the most detected song unit types recorded. Spectrogram parameters: Hann window with 50% overlap, 4,096 FFT size, 11.7 Hz resolution.

body of evidence showing humpback whale song production in winter feeding grounds in the North Atlantic. Humpback whales were acoustically detected in most months in our dataset. However, their acoustic occurrence peaked during summer (June and July), and late autumn to winter (October to March).

Icelandic waters are considered a key feeding habitat for the North Atlantic humpback whales during summer, since around 80% of the population was estimated to occur in these waters (Magnúsdóttir & Lim, 2019; Smith & Pike, 2009). The waters around the northeast and west of Iceland are known to be particularly important feeding grounds for the species (Cooke, 2018). Our study suggests that the Vestmannaeyjar archipelago in the south of Iceland is also an important region for humpback whales, probably as an extension of their summer feeding grounds. In July, the area is a herring spawning ground (Jakobsson & Stefánsson, 1999), which could explain the presence of humpback whales at that time of the year. Fish species are thought to be a crucial portion of humpback whale diet; a recent study of stable isotopes of baleen whales inhabiting Icelandic waters confirmed that humpback whales largely feed on krill and fish schools, with the latter composing 34% of their diet (Garcia-Vernet et al., 2021). Field observations in the area in summer confirm the presence of humpback whales, albeit in small numbers, feeding on herring (F.I.P.S., unpublished data).

Our study also indicates that the south of Iceland is an important area for the North Atlantic humpback whale during the winter season, possibly for whales coming from other regions of Iceland or elsewhere in the North Atlantic (Kettemer et al., 2022; Stevick et al., 2006). During February and March, capelin, a fish known to be targeted by humpback whales in Iceland (Garcia-Vernet et al., 2021), migrates to the south of Iceland to spawn (Astthorsson et al., 2007), and this coincides with a period of regular acoustic detections in our study. Humpback whale winter presence in our study area is supported by Kettemer et al. (2022) who showed that a humpback whale that was satellite-tagged in northern Norway spent several days in the east and south of Iceland en route to the Caribbean and suggested that Iceland constituted an important stop-over during its migration (Kettemer et al., 2022). The persistence of acoustic detections during winter may indicate the area is visited by late migrants from the eastern populations of the North Atlantic or by overwintering whales. This was also previously proposed by Magnúsdóttir & Lim (2019), Magnúsdóttir et al. (2014), and Tyarks et al. (2021) for northern Iceland and Norway, respectively. Past frequent occurrence of humpback whales in Norway throughout the year, with only a short migration out in spring for breeding, suggested that Northeast Atlantic whales may have a shortened breeding season (Christensten et al., 1990). Since we cannot distinguish between acoustic detections made by whales en route to or from breeding grounds or those from overwintering whales, combining acoustic recordings with other types of data (e.g., photo-ID) in the future would be useful to confirm this.

While humpback whales were detected during several months of the year, their vocal production changed throughout the seasons, changing from social calls in summer and fall to song fragments and songs in winter. The occurrence of social calls, typically associated with feeding and gregarious activities, is well documented in the literature (e.g., Dunlop et al., 2008; Fournet et al., 2015, 2018; Rekdahl et al., 2013), however, only a few studies have described these sounds extensively for the North Atlantic (Epp et al., 2021; Stimpert et al., 2011). In our study, the descriptions of social calls and song units recorded revealed a diverse call repertoire. Social calls were similar to those described elsewhere (Epp et al., 2021), however, a larger sample size will be needed to provide a comprehensive qualitative repertoire for the area. Song units classified in our study can be used for future comparisons to other regions in the North Atlantic, such as the one described by Tyarks et al. (2022) for northern Norway.

Song fragments are known to occur during the early months of the singing season in the western North Atlantic (Kowarski et al., 2019, 2021). Song fragments are characterized by few phrases or themes that are not repeated in a clear pattern, suggesting the possible way of how humpback whales gradually start the singing activity (Kowarski et al., 2019; McSweeney et al., 1989). Possible environmental cues have been hypothesized to trigger the singing process, such as photoperiod, temperature, body condition, food availability, or social interaction (Kowarski et al., 2021). Song fragments in our study area were also recorded at the beginning of the singing season, around mid-November. Kowarski et al. (2019) suggested that song fragments might reflect male practicing, immature males learning, or might be hormone induced. Due to the duty-cycled nature of the acoustic data in our study a detailed analysis of the song fragments was not possible. However, future investigations using continuous recordings could investigate song development and the drivers that trigger singing in humpback whales in the south of Iceland.

The presence of singing individuals was reported from November until late March. Songs were detected almost every day during the period from mid-January until March, with a peak in activity in February–March. Similar results were obtained by Magnúsdóttir & Lim (2019) for the north of Iceland and Tyarks et al. (2021) for northern Norway. The occurrence of song in southern Iceland suggests that, in the North Atlantic, migrations to lower latitudes are not associated to a strict time period (Mattila et al., 1987; Magnúsdóttir & Lim, 2019; Vu et al., 2012). This behavior has also been described for the North Pacific (Baker et al.,1985; Gabriele & Frankel, 2002; McSweeney et al., 1989). However, little information is available on the possible causes of late migration to breeding grounds, which might be related to environmental factors such as food availability or climate change (e.g., Brown et al., 1995; Craig et al., 2003; Dawbin, 1966; Kennedy et al., 2013; Straley et al., 2018; Vu et al., 2012). Recent studies have identified a correlation between climate anomalies and shifts in the migratory patterns of various whale species, including humpback whales (e.g., Külger et al., 2020; Cartwright et al., 2019; Moore, 2008). Significant changes in ocean conditions disrupt ecosystems, leading to cascading effects on food availability, which directly impact humpback whales. These alterations in food resources may affect migratory behavior, potentially delaying migration or even causing whales to skip migration due to reduced energy intake and lower body fat reserves (Külger et al., 2020).

This study did not find a diel pattern in the singing activity of the humpback whales visiting the south of Iceland. Magnúsdóttir et al. (2014) reported similar results for the north of Iceland. However, several other studies have shown a peak in singing activity during the nighttime (Au et al., 2000; Huang et al., 2016; Kowarski et al., 2018; Homfeldt et al., 2022; Shabangu & Kowarski, 2022), suggesting this might be a worldwide species characteristic (Au et al., 2000; Kowarski et al., 2019). In breeding grounds, individuals may rely on acoustic cues during the dark hours while they favor other competitive strategies that rely on light for visibility during the daytime and thus have less time for singing (Au et al., 2000). In our study site, competitive behaviors typical of breeding grounds might occur during daytime in February and March but no observations of such behavior have been made to confirm this. Future studies in this region should try to combine acoustic recordings with behavioral observations to investigate if singing behavior during winter months in feeding grounds may be less constrained to diel patterns than in breeding grounds. Another important factor to consider is the detection range: small-scale movements of individuals within the study area throughout the day may influence the ability to detect singing activity, as whales may move in and out of the detection zone at different times. For example, Külger et al. (2024) observed that diel patterns in humpback whale choruses are partly attributable to the offshore movements of singing individuals, rather than being solely driven by diel variations in vocal activity.

Studying humpback whale vocal behavior can be challenging due to the wide range of time-frequency characteristics of their sounds, which makes them difficult to distinguish from other ocean sounds and to classify them with confidence (Martin et al., 2015). In particular, social calls can be easily mistaken for background noise, due to their sporadic nature and typically lower source levels compared to song, as they might not be intended for long-distance communication (Au et al., 2006; Dunlop et al., 2008, 2013). The precision of the detector in south Icelandic waters was low, with only 2% of the detections being humpback whale sounds (Summer and Winter deployments combined). The precision of the detector varied with time depending on the levels of background noise and vessel traffic and was intentionally kept relatively low in order not to miss true detections. A detailed analysis of recall and accuracy of the detector was beyond the scope of this study, we only focused on ensuring the reliability for the target species.

Detector performance was strongly affected by the presence of killer whales. Similarly to humpback whales, killer whales produce sounds with a wide range of frequencies and in the Vestmannaeyjar archipelago, killer whales produce specific low frequency sounds (Samarra et al., 2016). This particular sound type was the most commonly misclassified sound by the detector during the Summer data set. In fact, the detector seemed to work better on the Winter data set, when vessel noise and killer whale calls were rarer. Likewise, manual detections of humpback whale calls were challenging when killer whale low frequency calls were present in the recordings, particularly if the quality of the sound was low. Humpback whales tagged in the summer at the same study site using multisensor DTAGs had a relatively low vocal rate (F.I.P.S., unpublished data). This aspect could have led to an underestimation of the humpback whale acoustic occurrence during summer, compared to winter, when humpback whales sing continuously for several hours.

Finally, the Winter deployment was collected with a duty cycle of 17%, unlike the Summer dataset collected in June to August which was recorded continuously. We acknowledge that this might have underestimated the occurrence of humpback whales, especially outside of the period with high levels of singing activity. In addition, an absence of humpback whale vocalizations cannot be considered an absence of occurrence of the species in the area, as animals may not always be vocalizing. On the other hand, the presence of high vocal activity also does not reflect a higher abundance of individuals either, as changes in behavior between seasons may simply lead to higher individual vocal rates. Future studies combining PAM with visual observations or using measurements of individual vocal rates at different times of the year should help address some of these challenges and help improve information on changes in humpback whale abundance throughout the season.

4.1 | Conclusion

Our results support previous studies showing the potential of PAM to reveal patterns in humpback whale occurrence and vocal behavior in remote or difficult-to-access regions, such as the subarctic waters off Iceland. It highlights the importance of the south of Iceland as a habitat for humpback whales, expanding the known feeding grounds for the species. The region may also be important as a stop-over site for migrating whales or as a potential overwintering area. A clear seasonal pattern in the acoustic behavior of humpback whales was found, varying between social calls and song production, in accordance with previous studies. This study also added to a growing body of evidence indicating that humpback whale song production does not just occur in breeding grounds but also occurs in feeding grounds. Future research using more comprehensive recordings from this region and comparisons with other regions in the North Atlantic should aid in a better understanding of acoustic behavior and song variation in the northern hemisphere.

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AUTHOR CONTRIBUTIONS

Carola Chicco: Data curation; formal analysis; investigation; methodology; visualization; writing – original draft; writing – review and editing. **Elena Papale:** Data curation; methodology; resources; supervision; writing – original draft; writing – review and editing. **Paul Wensveen:** Investigation; methodology; resources; writing – review and editing. **Xavier Mouy:** Data curation; resources; software; writing – review and editing. **Filipa Samarra:** Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; supervision; writing – original draft; writing – review and editing.

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SUPPORTING INFORMATION

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