

Article

Exploring the Occurrences of Beaked Whales off the West Coast of Ireland Through Passive Acoustic Monitoring (PAM)

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Abstract

Very little is known about goose-beaked whales (*Ziphius cavirostris*) and Sowerby's beaked whales (*Mesoplodon bidens*), especially off the western coast of Ireland, due to their elusive behaviors. This study aimed to characterize the acoustics of these beaked whales and investigate whether temporal patterns may affect their occurrences. Using passive acoustic monitoring (PAM), beaked whale bioacoustic clicks were manually analyzed, revealing different click frequency ranges than expected. Double clicks and echoes produced by both beaked whale species were also present, which have previously been infrequently observed in these species. The occurrence of beaked whales and the presence of double clicks and echoes were further investigated, along with how the diel cycle may affect these click characteristics. Hourly presence of goose-beaked whale double clicks and echoes was found to have significance for both day and night. There was no significance found for Sowerby's beaked whale double clicks and echoes for day and night, along with the hourly occurrences of both beaked whales and the occurrence of other beaked whales. These findings highlight the need for future research on PAM and beaked whale acoustics, which could aid in better monitoring of their presence to address the impacts of human activities.



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1. Introduction

1.1. Beaked Whales and Their Conservation Status

Marine conservation is emerging as an essential and necessary field for maintaining and developing ecosystems with “good environmental status”, which is reached when a marine environment is deemed healthy and biodiverse [1]. Effective management is a critical component for achieving the goals of the European Union's Marine Strategy Framework Directive [1]. Marine mammals may be utilized as indicators of “good environmental status,” especially baleen whales, toothed whales, seals, and mammals associated with ice [1]. New insight is needed, especially in the less-understood odontocete beaked whale family, the ziphiidae. Better knowledge of their habitat use, biology, population dynamics, behaviors, and ecology is also necessary [1–10] to understand species' interaction with an ecosystem and to guide conservation and management efforts [11]. Increased insight into beaked whale occurrences within their habitats and the environmental conditions that attract them can help conservationists decipher what factors may affect these species and how management practices can be implemented to reduce pressure on their population status and habitats [1,12–14].

However, this has yet to be easily documented for beaked whales, which remain an elusive family to observe visually, causing a lack of knowledge about this family [15]. Beaked whales are one of the least understood families of marine mammals, even though they comprise almost 25% of the known species of whales and dolphins [16,17]. All but three of the 24 species have unknown population trends [18], with new species being classified as recently as 2021 with the addition of Ramari's beaked whales (*Mesoplodon eueu*) [19]. This indicates that more information is needed to better understand the beaked whale family.

Beaked whales tend to be rare in deep abyssal basins and instead favor locations with variable bottom bathymetry [20], especially near slopes, escarpments, canyons, oceanic islands, ridges, and the continental shelf [6,21]. The Irish Atlantic Margin contains a suitable habitat for beaked whales, has a complex bathymetry, and is one of the highest biologically productive regions of the northeast Atlantic with high prey availability [22]. This area has upwelling, persistent eddy systems, the North Atlantic currents, and the continuous shelf edge currents that concentrate prey [22]. There are about 26 cetacean species found in Irish waters, including beaked whales [23]. The most frequently detected beaked whale species in Ireland, especially around the Rockall Trough margin, is the goose-beaked whale (*Ziphius cavirostris*) [24] off southwest Ireland, with Sowerby's beaked whales (*Mesoplodon bidens*) off northwest Ireland [3,10,12,25]. The Irish Atlantic Margin may be very important, specifically to goose-beaked whales and Sowerby's beaked whales, for breeding sites compared to other beaked whales [26].

1.2. Threats for Beaked Whales

However, there have been higher levels of beaked whale strandings off the coast of Ireland in the past twenty years, with many occurring during heightened naval activity in the region [27]. Navy mid-frequency active sonar (MFAS) exercises have especially led to the disproportionately large mass strandings of goose-beaked whales worldwide [21,28], with likely long-term effects [29]. Along the Irish Atlantic Margin, there has also been an increase in seismic airgun surveys for oil exploration [30,31]. These are of particular concern off the coast of Ireland, as its unique water mass properties and extreme sloping bathymetry may significantly increase the magnitude of anthropogenic noise toward the depths of the nearby canyon [32–34].

Goose- and Sowerby's beaked whales are also threatened by echosounders, entanglement, vessel strikes, persistent organic pollutants (POPs), toxic metals, plastics, and oil spills [34], which they may encounter in this region. With climate change and higher sea surface temperatures, a range shift in cephalopod biodiversity, their primary prey source, is also expected in the northeast Atlantic [35]. This may lead to negative consequences for goose-beaked whales [36], which have a high site fidelity [37], and Sowerby's beaked whales, which are range-restricted [21]. However, the current lack of information on these beaked whales will make it difficult to understand how these threats will affect them [38]. There is also little understanding of how different species of beaked whales interact with their habitats and the biotic and abiotic factors associated with them [39–43]. A clearer understanding of where and when these beaked whales occur can lead to more effective monitoring practices, especially by informing the timing and location of increased anthropogenic noise.

1.3. Passive Acoustic Monitoring of Beaked Whales

Habitat use of beaked whales is challenging to understand, as they spend limited time on the surface and have a deep-water habitat use [44], and the blows they exhale can be nearly invisible to observe [45]. Therefore, even though it is estimated

that beaked whales are only acoustically active 20% of the time in an area, bioacoustic monitoring can detect more beaked whales than visual surveys [44,46,47]. Bioacoustic monitoring allows for the detection of sounds from a distance, with a more robust understanding of population dynamics and behaviors, while limiting the effects of researchers' presence [9,44]. One method is passive acoustic monitoring (PAM), which records species actively vocalizing in a specific range of the device [48]. Generally, each beaked whale species produces unique echolocation clicks from each other, making species identification possible using bioacoustics [49].

1.4. Research Objectives

Using bottom-mounted passive acoustic monitoring, this study focuses on manually characterizing the bioacoustic echolocation clicks of goose-beaked whales and Sowerby's beaked whales off the coast of Ireland, to better describe the vocalizations of Irish beaked whale populations, for the first time. The goals of this study were to provide new insights into acoustically detecting these species in a less-studied area and to determine temporal patterns of their occurrences. This study also aims to better describe the click characteristics of these species off the west coast of Ireland and compare them to those of each species. Understanding these factors can help monitor beaked whale occurrences, which can help guide mitigation efforts for these species in response to anthropogenic noise that may increase in this region.

2. Materials and Methods

2.1. Acoustic Data Collection and Processing

The Department of the Environment, Climate and Communications (DECC) and the Department of Environment, Heritage and Local Government (DEHLG) initiated the OBSERVE Acoustic project along the Irish Atlantic Margin. Eight moorings with Autonomous Multichannel Acoustic Recorder (AMAR) units (JASCO Applied Sciences, Halifax, NS, Canada) were deployed during four phases, ranging from May 2015 to November 2016, following the contours created from the unique bathymetry of the Rockall Trough, the Porcupine Bank, and the Porcupine Abyssal Plain. This survey revealed two beaked whale species: goose-beaked and Sowerby's beaked whales, and a handful of northern bottlenose whales (*Hyperoodon ampullatus*) [31,50]. The mean daily detections were higher for both goose- and Sowerby's beaked whales at Mooring Four [31,50], which was chosen for further acoustic analysis (Figure 1). A schematic diagram of this study's methodology is presented in Figure 2.

Mooring Four was on a slope at a depth of 1920 m, sampled from 7 May to 30 August 2015, at 54.00138 and −14.04242 decimal degrees. The recorder was suspended about 25 m above the seafloor using a dual acoustic release array, which included an HTI-99-HF omnidirectional hydrophone (High Tech Inc., Long Beach, MS, USA). An acoustic recorder at this depth can detect echolocation clicks produced by beaked whales during foraging dives [14]. To measure the presence of species that produce higher frequencies, like beaked whales, the data was sampled at a higher frequency channel at 250 kilo samples per second (ksps) for a sampling time of 130 s, collected every eight minutes, creating a recording bandwidth of 125 kilohertz.

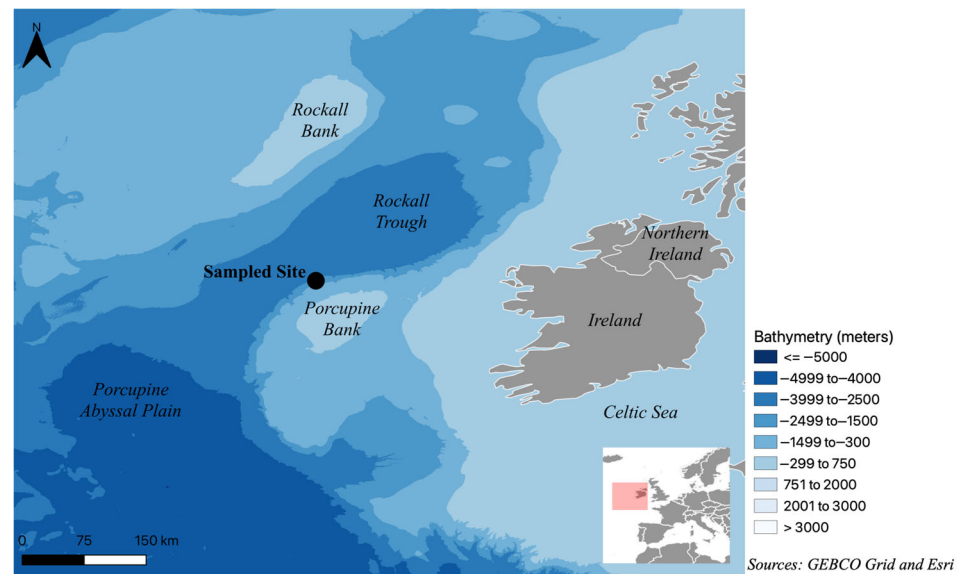


Figure 1. The deployment site of the acoustic receiver chosen for this study. Data was obtained from GEBCO Grid and Esri. Map created using QGIS 3.20 Odense.

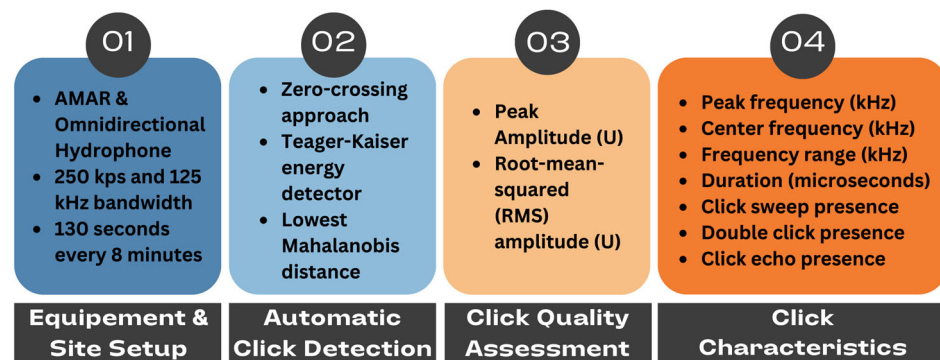


Figure 2. Schematic diagram of the materials and methods used in this study.

2.2. Raven Manual Click Annotation

Automatic click detections for all species were processed prior by JASCO, using a zero-crossing approach, a Teager-Kaiser energy detector, and selecting detections with the lowest Mahalanobis distance [31,50]. Each sample file for this site, containing detected clicks of goose-beaked whale or Sowerby's beaked whale, was further reviewed manually to validate the clicks accurately and was of the highest quality for analysis. An occurrence of a beaked whale was defined as having one or more detected clicks in an hour. "Occurrences" denotes the presence of clicks from a species that was present and acoustically active in the area being recorded and is not related to the relative abundance of the species [47]. These beaked whale clicks were processed using the sound analysis software Raven Pro 1.6.4 (© Cornell Lab of Ornithology). The view of the spectrogram of the clicks was set to a Hann window, a -3 decibel (dB) filter bandwidth at 703 hertz (Hz), a time overlap of 50%, and a hop size of 256 samples. The discrete Fourier transformation frequency size was set to 512 samples, grid spacing of 488 Hz, brightness of 45, and contrast of 85.

The peak amplitude (U) and the root-mean-squared (RMS) amplitude (U) were used to help select the highest-quality clicks for each sample. Each click was annotated with its corresponding peak frequency (kHz) and center frequency (kHz). Each click's frequency range (kHz) was calculated by taking the difference between the high and low frequencies (kHz). Click duration accounted for the difference between the start and end time in microseconds. This is difficult to compare with other studies, as it is calculated differently

depending on the study [49,51–53], so subsequent comparisons were not made for this variable. However, as goose-beaked whales tend to have longer click durations than other species with similar frequencies, like northern bottlenose whales, it helps differentiate between them acoustically [53].

Each click was also annotated as having the presence or absence of a sweep (frequency-modulated (FM) sweep pulses), as upsweeps have been observed among beaked whales [54], with downsweeps identified in goose-beaked whales [55]. Each sample was also analyzed for the presence or absence of echoes and double clicks. Clicks produce echoes when they bounce off the seafloor and are received when they return to the bottom-mounted receiver [56]. Double clicks are when one click is observed, with a second click immediately detected after the first [57].

2.3. Temporal Covariates

The diel cycle was recorded to determine the temporal habitat use of the beaked whales and how their click characteristics may alter depending on the time of day. The diel cycle was calculated for each beaked whale detection, with each hour categorized as day or night in conjunction with sunrise and sunset. Daytime was determined from when the sun was 12° below the horizon until sunrise, along with the hours of sunlight. Nighttime was determined from when the sun was more than 12° above the horizon until sunset, along with the hours of darkness. The exact times for these were obtained from Reda and Andreas (2004) [58], which were about 7:00 to 19:00 for daylight and 19:00 to 7:00 for night for the area.

2.4. Data Analysis

Once the click characteristics were extracted, descriptive statistics (mean, standard deviation, 10th percentile, and 90th percentile) were calculated with R version 4.2.2 (R Core Team). The Shapiro-Wilks test was then applied to each variable for each species to assess normality and inform the selection of the appropriate statistical analysis. The variables investigated included the diel cycle and the hourly presence of double clicks and echoes for each species. Although the data was limited, an investigation into the hourly occurrences of goose- and Sowerby's beaked whales was undertaken to initiate an understanding of how their occurrences might have influenced each other. As the data for the variables chosen were not normally distributed, a Kruskal–Wallis analysis of variance was used for each variable as a non-parametric alternative to ANOVA. Finally, the significance of the resulting chi-square statistic was used to indicate if the two variables differ from each other based on the rank used. A Mann–Whitney U post hoc test was then conducted for variables that showed significance in the Kruskal–Wallis analysis.

3. Results

3.1. Beaked Whale Click Characteristics and Occurrences

Clicks from the initial detection analysis were selected manually during Raven analysis to accurately identify clicks to the species level and select the best data for click characterization. The maximum detection range for the complete dataset was previously calculated as up to 14 km for goose-beaked whales and 4 km for Sowerby's beaked whales [50]. During the sampled period, 116 days of sampling effort were collected and used for this study, recording approximately 683 h of acoustic data. There were 1690 goose-beaked whale clicks (Figure 3A,B) and 898 Sowerby's beaked whale clicks (Figure 3D,E). Double clicks (Figure 3C,F) were observed in samples containing goose-beaked whales in 72 of the 401 sample files (18%). Echoes (Figure 3G,H) accounted for 154 of the goose-beaked whales' sample files (38%). Conversely, double clicks accounted for 8 of the 249 sample files (3%)

and echoes of 6 (2%) for Sowerby's beaked whales. No sweeps were indicated for either species in the samples reviewed.

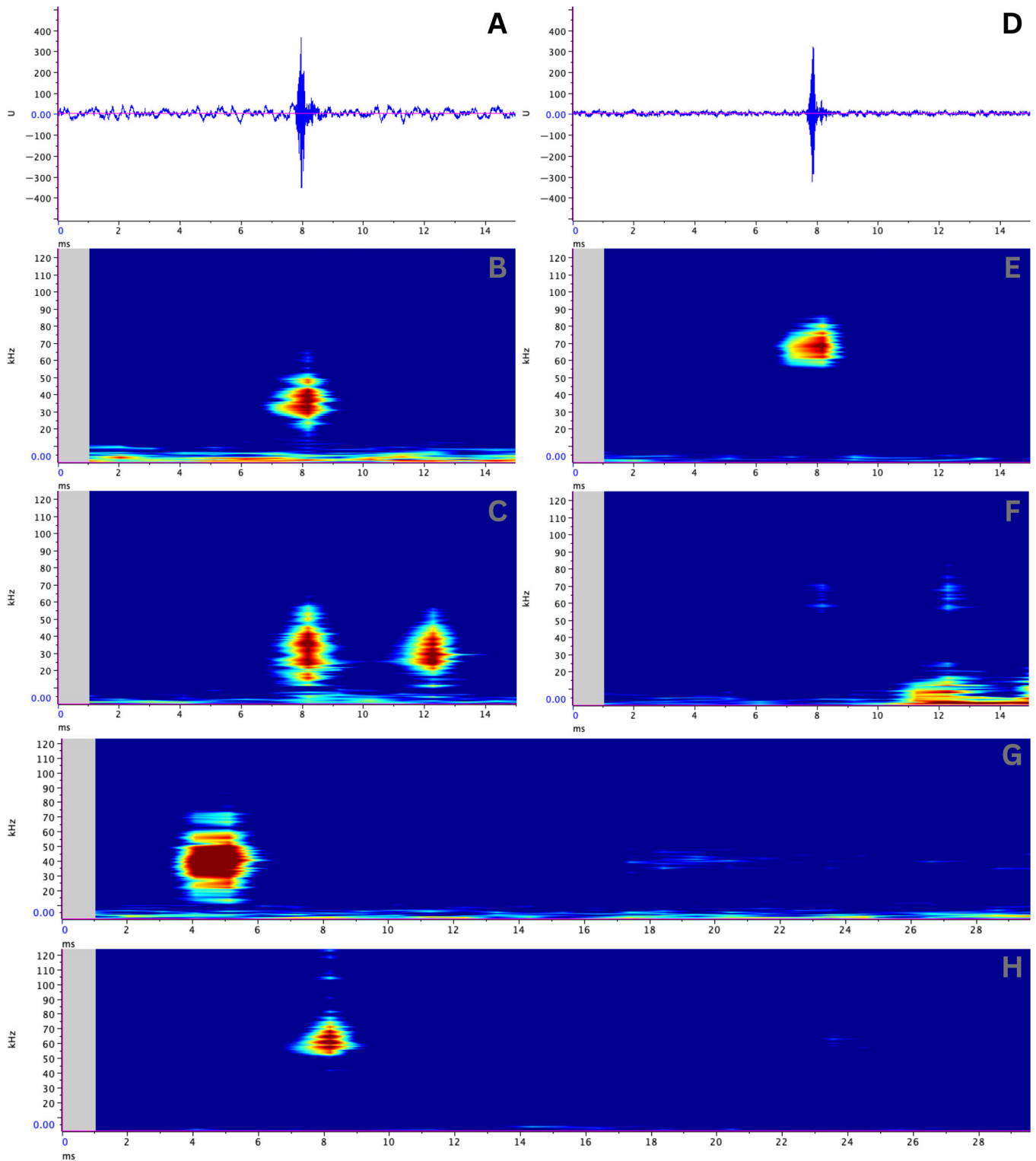


Figure 3. Click amplitude (A), click frequency (B), and double clicks (C) of a goose-beaked whale. Click amplitude (D), click frequency (E), and double clicks (F) of a Sowerby's beaked whale. Echoes from the goose-beaked whale click (G) and Sowerby's beaked whale click (H). Images created in Raven with milliseconds (ms) on the x -axis and kilohertz (kHz) on the y -axis. Color denotes the relative spectral level (dB FS/Hz), with higher levels as red and lower levels as blue.

For the goose-beaked whale clicks, the mean peak frequency sampled was 38 kHz (± 4 kHz), the mean center frequency was 38 kHz (± 3 kHz), the mean frequency range was 69 kHz (± 21 kHz), and the mean duration was 2837 microseconds (± 847 microseconds). The mean peak amplitude was 656 U (± 942 U), and the root-mean-squared (RMS) amplitude mean was 75 U (± 88 U). For the Sowerby's beaked whale clicks, the mean click peak frequency was 65 kHz (± 4 kHz), the mean center frequency was 66 kHz (± 2 kHz), the mean frequency range was 37 kHz (± 11 kHz), and the duration mean was 1649 microseconds (± 400 microseconds). The mean peak amplitude for this species was 117 U (± 70 U), and the RMS amplitude mean was 20 U (± 10 U) (Table 1 and Figure 4).

Table 1. Descriptive statistics of analyzed goose-beaked whale clicks for the sampling period (a) and Sowerby's beaked whale clicks for the sampling period (b).

	Goose-Beaked Whale			Sowerby's Beaked Whale		
	N = 1690			N = 898		
	Mean $\pm$ Standard Deviation	10th Percentile	90th Percentile	Mean $\pm$ Standard Deviation	10th Percentile	90th Percentile
Peak Frequency (kHz)	38 $\pm$ 4	35	41	65 $\pm$ 4	60	71
Center Frequency (kHz)	38 $\pm$ 3	35	40	66 $\pm$ 2	63	69
Frequency Range (kHz)	69 $\pm$ 21	43	98	37 $\pm$ 11	27	51
Duration (Microseconds)	2837 $\pm$ 847	1845	3914	1649 $\pm$ 400	1190	2234
Peak Amplitude (U)	656 $\pm$ 942	129	1263	117 $\pm$ 70	56	204
RMS Amplitude (U)	75 $\pm$ 88	21	139	20 $\pm$ 10	12	33

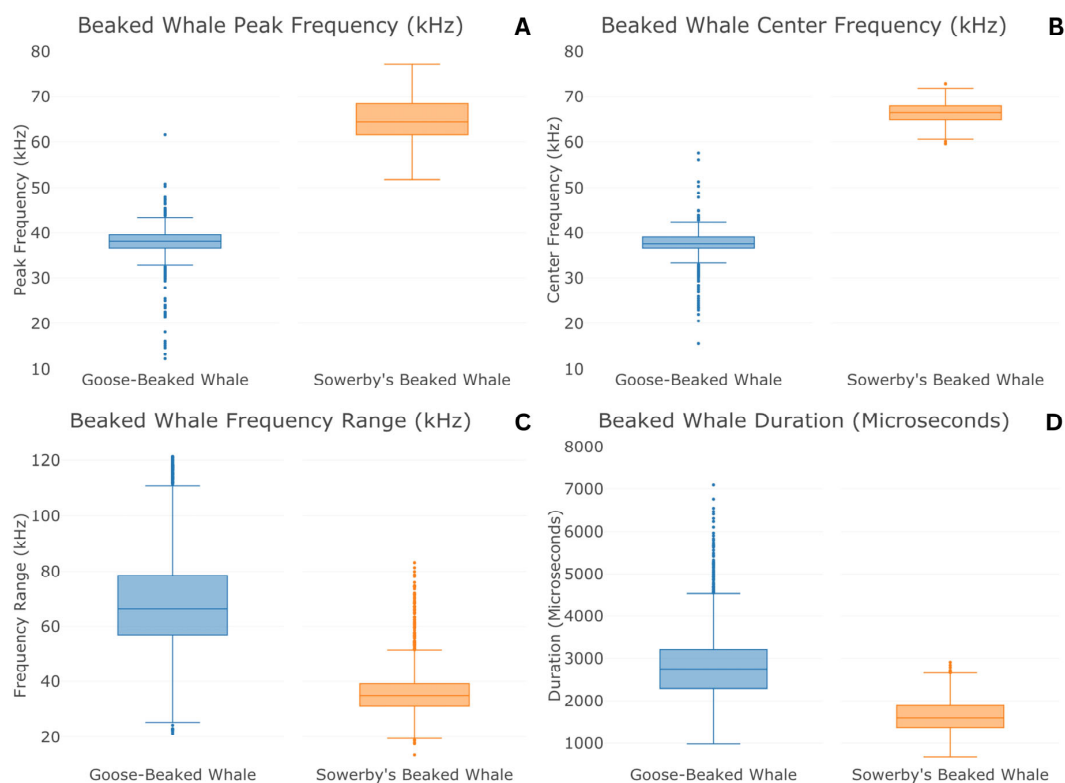


Figure 4. Box plots of goose-beaked whale and Sowerby's beaked whale click peak frequencies (kHz) (A), click center frequencies (kHz) (B), click frequency ranges (kHz) (C), and click durations (microseconds) (D).

The overall occurrence of beaked whales in the sample varied by time and day, with some periods exhibiting high occurrences and others showing no detected clicks. Goose-beaked whale occurrences had higher peaks than Sowerby's (Figure 5). Both species occurred more often during the day, with decreased occurrence at night. Goose-beaked whale clicks during the day accounted for 1182 clicks (70%), with 653 (73%) Sowerby's beaked whale clicks. Among hours with goose-beaked whale double clicks, 41 of the 58 (71%) occurred during the day and 17 (29%) occurred during the night. Goose-beaked whale echoes during the day accounted for 87 of the 122 (71%) detected hours, and 35 (29%) at night. For Sowerby's beaked whale double clicks, 4 of the 7 (57%) occurred during the day and 3 (43%) occurred during the night. Sowerby's beaked whale echoes during the day accounted for 6 of the 6 (100%) detected hours, and none occurred at night (Figure 6). For each species, these occurrences further differed, with detections for each species rarely co-occurring within an hour of each other. Of the 648 sample files with either species, only 36 (6%) of the sample files had both species co-occurring within an hour.

Beaked Whale Occurrence

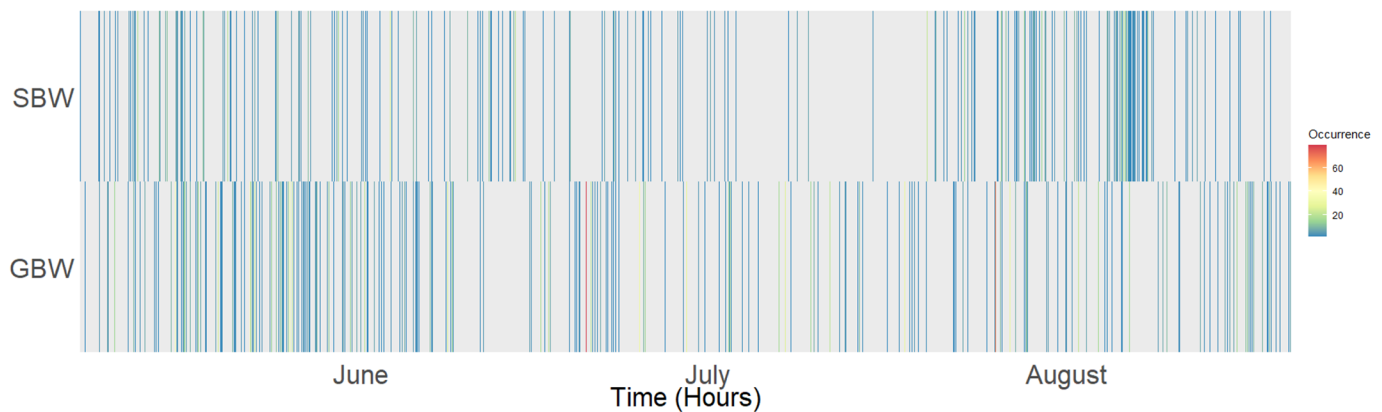


Figure 5. Total beaked whale occurrences, each line representing the hourly sum for goose-beaked whales (GBW). And Sowerby's beaked whale (SBW). Gray indicates no occurrence.

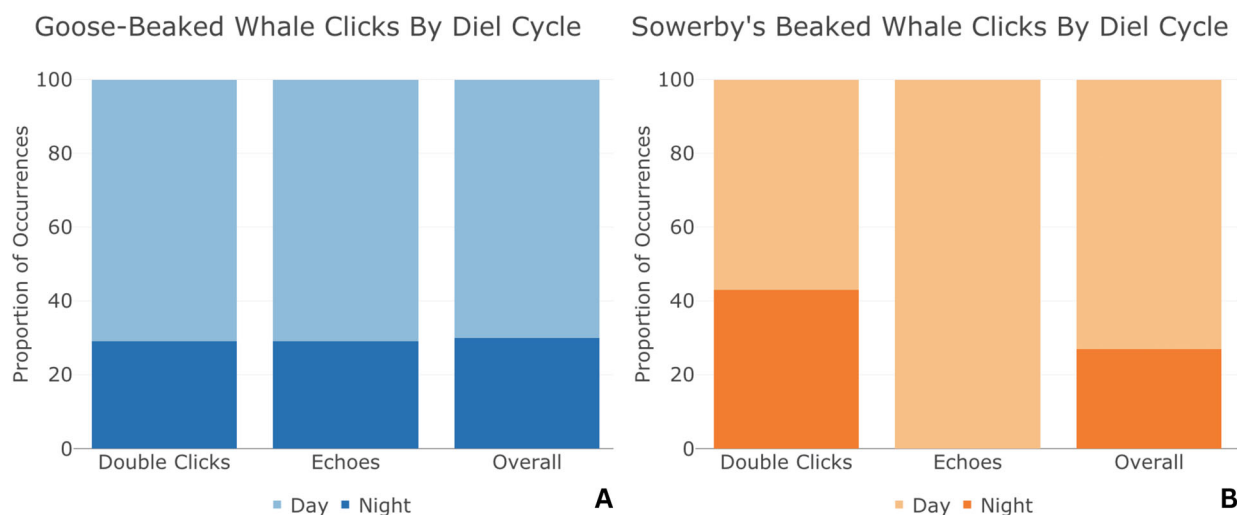


Figure 6. Proportion of beaked whale occurrences for each diel cycle of goose-beaked whales (A) and Sowerby's beaked whales (B) for the overall data, and out of the total amount of hours with double clicks and echoes for each species.

3.2. Statistical Analyses

A Shapiro-Wilks test for normality was carried out, and all covariates used for the models were not normally distributed (p -values ≤ 0.05) and were resistant to transformations toward normality. As the data was non-linear, a Kruskal–Wallis analysis of variance was used, which indicated that the occurrence of goose- and Sowerby’s beaked whales had no statistical significance between each other. There was no significance found for either goose- or Sowerby’s beaked whale hourly occurrence in terms of diel cycle, or Sowerby’s beaked whale hourly presence of double clicks and echoes. However, goose-beaked whales showed significance (p -values ≤ 0.05) for the hourly presence of double clicks and echoes. Significance was found (p -values ≤ 0.05) from Mann–Whitney U post hoc tests using hourly occurrence of goose-beaked whales during the day and night, with hourly presence of double clicks and echoes.

4. Discussion

4.1. Click Characteristics of Irish Beaked Whales

This study presents the first in-depth analysis of the click characteristics of beaked whales off the coast of Ireland. It provides new insights into how these populations use echolocation compared to other populations. The site for this study encompassed the southern boundary of Sowerby’s beaked whales and the northern boundary of goose-beaked whales off western Ireland, which may be prey-driven [3,22,31,50] and likely represents a meeting point between the two species and other species in the area. As the click characteristics of both species had not previously been analyzed in such detail off the coast of Ireland, this study adds to the current knowledge of beaked whale acoustics and their occurrences.

The clicks of goose-beaked whales indicated peak and center frequencies similar to those found in other studies, although their frequency range was more variable and higher on average [16,47,51,53,56,59–62]. The variations in goose-beaked whale frequency ranges may be due to the ability to manually identify more details from the data than a detector, resulting in longer and higher values for each click. The variation may also be because beaked whales move their heads up, down, and side-to-side during foraging [59], which may affect the quality of the click data [13,53]. This potentially causes the echolocation not to be directed toward the receiver [63], limiting the full capture of clicks [52], and causing the acoustic receiver to miss some detections. This also may present unique characteristics for Irish goose-beaked whales, where the frequency ranges may differ from other areas.

For Sowerby’s beaked whale clicks, the peak frequencies, center frequencies, and frequency ranges were similar to those found in previous studies [49,57,61,64]. The peak frequency for Sowerby’s beaked whales, on average, followed the high peak frequency group first categorized by Cholewiak et al. (2013) [57] and later identified by Clarke et al. (2019) [64] and Cohen et al. (2022) [61]. This suggests that Sowerby’s beaked whales off the coast of Ireland may present similar peak frequencies to those of other populations. Cholewiak et al. (2013) [57] may have studied a unique population or unique local characteristics with more variation. A recent study was the first to find the lower peak frequencies that Cholewiak et al. (2013) described in their study [57,65]. This also suggests that such detections may be more easily identified in higher groupings, as these clicks are distinctive compared to other species.

4.2. Diel Cycle and Click Characteristics of Beaked Whales

Significance was found for goose-beaked whale echoes, for both day and night, but no significance was found for Sowerby’s beaked whales. This may be due to echoes being observed primarily with goose-beaked whale clicks and only faintly, a few times for

Sowerby's beaked whales. This might be because goose-beaked whales specifically have higher source levels, allowing their clicks to travel further and reach the seafloor more easily [50,66]. Echoes are easier to distinguish from the seafloor [50] and can be due to the forward-directed sonar beams of beaked whales and their active downslope swimming behavior as they forage [67]. This may be why echoes were observed in this study set on a slope, and it may indicate periods of active foraging along the slope. The returned echoes can help the beaked whale identify their surroundings and locate targeted prey [68].

Observations of double clicks of both species are unique and have not been obtained in most studies [57,69]. Goose-beaked whale double clicks showed significance, for both day and night, but no significance was found for Sowerby's beaked whales. The reasons for the presence of double clicks, their purpose, and whether this is specific to certain populations or times are still being determined. There were no click sweeps observed in this dataset, which could be due to the population in Ireland having different click characteristics or due to sampling a phase when they may not use sweeps, as compared to other studies that observed them [54,55,66].

Regarding the diel cycle, the number of occurrences of goose- and Sowerby's beaked whales present during the day was almost double that occurring at night, but did not show significance in the results. As the mooring was located 1920 m deep, perhaps the increased activity during the day at this depth resulted from the beaked whales spending more time foraging at deeper depths during the day than at night. The preference for foraging in daylight has been observed in other studies [70,71]. One explanation is that beaked whales avoid visually oriented predators that prefer to hunt with light [72] and spend more time in shallow depths at night when it could be safer from predators [40,73–82]. However, the lack of statistical significance points to other possible factors influencing beaked whale occurrences in the study area.

4.3. Beaked Whale Habitat Partitioning

Among beaked whales, their occurrence did not have any significance on the occurrence of other beaked whales. Within the dataset analyzed, there were only 36 co-occurrences of goose-beaked whales and Sowerby's beaked whales within an hour of each other, which may have accounted for a lack of significance among goose- and Sowerby's beaked whale co-occurrences. Goose-beaked whales have not been observed to cease echolocating in the presence of conspecifics [75], and so this was not likely a reason for this possible lack of a relationship. It is also unclear if the presence of other beaked whales or cetaceans would affect their vocalizations. There is already a strong habitat partitioning of the two species in this area [3,22,31,50], which might be prey-related or due to some other factor. There has only been one observation of these two species co-occurring, where two likely stray Sowerby's beaked whales were associated with local goose-beaked whales in the Tyrrhenian Sea, and this suggests cooperation is possible if needed [39].

Among beaked whales, goose-beaked whales, and Sowerby's beaked whales do not have any trophic niche overlap by mass or number, which may allow them to forage in similar areas [76]. It has been observed that beaked whales have ecological niches and fine-scale habitat partitioning when sharing foraging grounds with other cetaceans [47]. The average foraging dive for a goose-beaked whale is roughly 700 to 2000 m deep [9,16,40,71,73,77,78], with the deepest recorded dive for this species by one individual reaching a depth of 2992 m [74]. In comparison, Sowerby's beaked whales are found at depths ranging from about 400 to 1400 m [9,21,49,79]. The differences in depths during foraging suggest it is likely prey-driven.

Goose-beaked whales primarily feed on oceanic bioluminescent mesopelagic and bathypelagic squids [80,81], which migrate to deeper depths during the day [82]. Their

body mass and use of aerobic and anaerobic respiration, with longer inter-deep dive intervals, aid the increased dive times to catch prey [83]. The depths and durations of their dives may depend on location, as influenced by the prey type, density, or behavior [40]. The diet of Sowerby's beaked whales is almost entirely mesopelagic and benthopelagic fish, with some cephalopods [84]. They forage opportunistically with little preference, feeding on prey abundant in midwaters [81,85]. This may help fill feeding niches in response to competition [49], as Sowerby's beaked whales have a habitat preference similar to that of sperm whales [84]. The feeding preferences of both beaked whales indicate a possible reason for their habitat partitioning and the lack of a relationship between the two species.

4.4. Limitations, Recommendations, and Future Perspectives

Previous research used the extensive dataset from the ObSERVE Acoustic project, which initially documented habitat partitioning among beaked whales off the west coast of Ireland [22,31,50]. As this study focused only on one location on a slope during a single sampling period, it did not consider seasonal changes or differences in habitat types. These factors could influence the habitat partitioning observed at this site and the relationships of the variables explored. Additionally, acquiring information on the amount and geographic distribution of prey for beaked whales would help determine if prey availability drives certain beaked whales across the Irish Atlantic Margin. Gaining a better understanding of whether specific prey are more vital to these species could clarify the mechanisms behind the habitat partitioning between goose- and Sowerby's beaked whales. As interspecific interactions of beaked whales are still unknown, it is important to begin understanding how the presence of other species may affect them. These interactions may be primarily prey-driven, and gaining a better understanding of the prey choice of cetaceans in Irish waters can help begin to address these questions.

This study exemplifies that bioacoustics, such as PAM, is an essential and necessary tool for the comprehensive study of beaked whales, which are challenging to study using other methodologies. PAM allows for many months of data to be collected across all 24 h, while visual observations are limited to daylight hours and are less efficient for elusive species, such as beaked whales. This study was able to describe their click characteristics and the influence of temporal patterns on their acoustical occurrences. Double clicks and echoes were observed in this study, giving new insight into beaked whale acoustics in western Ireland. These findings can help acoustically monitor future occurrences of goose- and Sowerby's beaked whales, which can help guide more effective management practices. Knowing where and when these whales are present can help determine the best timing and location for conducting certain surveys. It is well established that MFAS and seismic surveys harm beaked whales [28,29,34,86–91], which may increase in the future in this region. Therefore, this study emphasizes the need for future research into the effectiveness of acoustically detecting beaked whales with PAM, which could support the protection and well-being of these whales. Understanding these factors can guide new regulations to reduce threats, including marine spatial planning and the creation of binding guidelines for visual and acoustic surveys during activities that increase the anthropogenic noise of the surrounding area [92–94]. Using PAM for detecting beaked whales can help make mitigating the harmful effects of anthropogenic noise more effective.

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Data Availability Statement: Data availability for this study is available through the Irish Department of Communications, Climate Action and Environment. Data can be accessed at <https://www.gov.ie/en/publication/12374-observe-programme/#project-data> (accessed on 8 February 2023).

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AIC	Akaike Information Criteria
AMAR	Autonomous Multichannel Acoustic Recorder
DECC	Department of the Environment, Climate and Communications
DEHLG	Department of Environment, Heritage and Local Government
GAM	Generalized Additive Model
GBW	Goose-Beaked Whale
MFAS	Mid-Frequency Active Sonar
PAM	Passive Acoustic Monitoring
POPs	Persistent Organic Pollutants
REML	Restricted Maximum Likelihood
SBW	Sowerby’s Beaked Whale

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