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Sperm whale acoustic ecology around two sub-Antarctic islands

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ABSTRACT

Sperm whales are cosmopolitan in nature, but very little is known about their occurrence in the sub-Antarctic region. This study aimed to investigate the acoustic occurrence of sperm whales relative to environmental conditions and underwater noise around two sub-Antarctic Prince Edward Islands (PEIs) using passive acoustic monitoring data collected between early 2021 and early 2023. Sperm whale clicks were detected continuously throughout the study period with high presence of calls in February through August, highlighting the PEIs as an essential habitat with sufficient year-round prey for this species. Moreover, the February through August peak occurrence corresponds to the migration period of males from Antarctica to the low latitudes for mating. Diel vocalizing pattern revealed high nighttime vocalization that varied slightly between seasons. Wind speed was classified by the random forest model as the most important predictor of sperm whale acoustic occurrence, indicating possible masking and attenuation of whale signals by wind-induced noise and wind-induced air bubbles respectively. Generalized additive model showed that the probability of detecting sperm whale clicks decreased with increasing high frequency band (25001–48000 Hz) noise, reflecting a significant influence of the high frequency noise on this species' ecology. This is the first study to document the acoustic presence of sperm whales around the sub-Antarctic PEIs, showcasing the capability of bioacoustics method to effectively study marine mammals that are rarely sighted. Sperm whales should be considered in the spatial management and conservation plans of the PEIs given their year-round presence in this region.

1. Introduction

Sperm whales (*Physeter macrocephalus*) are the largest of all toothed whales with a cosmopolitan distribution, and are generally found, but not exclusively, in waters deeper than 200 m (Best, 2007). Seasonal movement and migration of the species vary between sex and age composition of groups (Best, 1979, 2007). Adult female sperm whales (including calves and juveniles) move seasonally between low and mid-latitudes (i.e. between 40°N and 40°S) and rarely venture into polar regions (Matthews, 1938; Best, 1969, 1979, 2007). These females form matriarchal family groups termed clans or social units that practice alloparental care including babysitting (Best, 1979; Whitehead, 1996, 2024). On the other hand, juvenile males form "bachelor herds" while older males are solitary and migrate between the low latitudes and polar regions for mating and feeding respectively (Matthews, 1938; Best, 1969, 1979, 2007). Final destinations of males in the Southern Ocean are not fully known, with recent evidence indicating seasonal presence (Miller and Miller, 2018) while another study indicates year-round presence (Giorli and Pinkerton, 2023). Only one acoustic study on sperm whale presence exists in the sub-Antarctic region (Miller et al., 2024), which found sperm whales from September through March. The current study reports on another location in the poorly studied sub-Antarctic region of the Southern Ocean, the Prince Edward Islands (PEIs).

The PEIs are located halfway between Antarctica and Africa (Fig. 1) and are part of the Southern Ocean in the southwestern Indian Ocean sector. Marion Island and Prince Edward Island collectively make up the PEIs archipelago. Due to the biological productivity around the PEIs, these islands are used by numerous seabirds, fishes, and marine mammal species as a breeding, foraging, overwintering, and year-round habitat (Reisinger et al., 2018; Shabangu et al., 2024a, 2024b; Shabangu et al., 2025a). The PEIs are a multi-use zone marine protected area (MPA) declared in 2013, and this MPA consists of one sanctuary zone, four restricted zones, and controlled zones between restricted zones (Lombard et al., 2007). Only one fishery operates within the exclusive economic zone (EEZ) of the PEIs: the Patagonian toothfish (*Dissostichus*

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eleginoides) longline fishery, which is managed by the South African Department of Forestry, Fisheries and the Environment using the Operational Management Procedure (Brandão and Butterworth, 2021). This PEIs' Patagonian toothfish fishery management also considers conservation measures of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). Interactions and relationships between the Patagonian toothfish fishery and sperm whales in the PEIs have, to date, been studied only through visual sighting cues (Tixier et al., 2020). As such, there is a big knowledge about the acoustic ecology of sperm whales in this part of the Southern Ocean.

Sperm whales produce a variety of broadband (10 Hz–30 kHz; André et al., 2017) clicks (usual, slow, creaks/buzzes, and codas) that are used for communication and echolocation (e.g. Watkins and Schevill, 1977; Jaquet et al., 2001; Madsen et al., 2002; Oliveira et al., 2016; Sharma et al., 2024). Characteristics of communication-geared clicks, codas, that are emitted by both sexes, differ between allopatric sperm whale social groups, creating what is called vocal clans (e.g. Rendell and Whitehead, 2003; Whitehead, 2024). Codas contain important pertinent information specific to sperm whale social structure and behaviour (Whitehead and Rendell, 2004; Sharma et al., 2024; Whitehead, 2024). Slow clicks are specifically used by males for communication (Madsen et al., 2002; Oliveira et al., 2016). Echolocation clicks such as creaks and usual clicks (used by whales to zone in and capture prey) can be used by researchers to estimate the size or demography of vocalizing whales based on interpulse interval (e.g. Giorli and Goetz, 2020; Miller et al., 2024; Westell et al., 2024). Additionally, both echolocation and communication clicks can be used to study the occurrence, movement, and habitat use of sperm whales in relation to environmental conditions and underwater noise (Whitehead and Rendell, 2004; Miller and Miller, 2018; Shabangu and Andrew, 2020; Shabangu et al., 2022; Giorli and Pinkerton, 2023; Miller et al., 2024; Pöyhönen et al., 2024; Westell et al., 2024).

Through this study, I aim to 1) estimate the acoustic occurrence of sperm whales, 2) determine the diel vocalizing pattern of sperm whales, 3) determine the influence of environmental conditions on sperm whale acoustic occurrence, and 4) investigate the relationship between sperm whale acoustic occurrence and underwater noise around the sub-Antarctic PEIs.

2. Materials and materials

2.1. Acoustic data collection and processing

Passive acoustic monitoring data were collected halfway between Marion Island and Prince Edward Island, the Prince Edward Islands (Fig. 1), using a SoundTrap ST500 STD acoustic recorder (Ocean Instruments, New Zealand) that was deployed on an oceanographic mooring to study baleen whales (Shabangu et al., 2024b). The oceanographic mooring (setup of the mooring is described in Shabangu et al. (2024a)) was deployed at a water depth of ~167 m, and the acoustic recorder was positioned 5 m from the seafloor (Table 1). The acoustic recorder was set to record on a 28 % duty cycle and a sample rate of 96 kHz over the two years (Table 1). The collected passive acoustic data were decimated from 96 to 9.6 kHz to improve the frequency resolution and the discrete Fourier transform (DFT) length of sounds when analysing baleen whale calls (Shabangu et al., 2024b). These passive acoustic data were decimated using 'PAMmisc' package (Sakai, 2024) in R (version 4.4.1; R Core Team, 2024).

Passive acoustic data were analysed in Raven Pro (K. Lisa Yang Center for Conservation Bioacoustics, 2025) through visual review of spectrograms (Fig. 2) using a Hann window with a frame size of 0.487 s, 90 % overlap, and DFT size of 8192 samples. Sounds of interest were

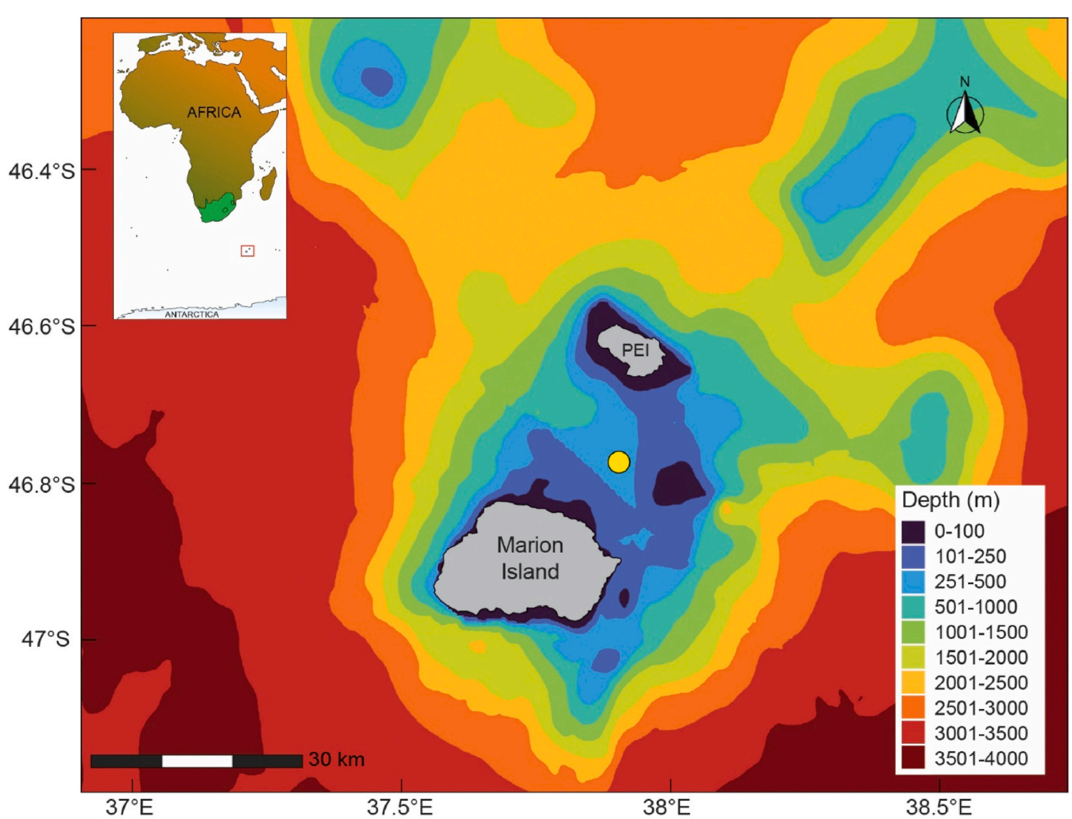

Fig. 1. Position of the oceanographic mooring with the acoustic recorder (yellow circle) deployed between Marion Island and Prince Edward Island (PEI), comprising the Prince Edward Islands (PEIs). Inset map shows the PEIs (red rectangle) relative to South Africa (green shading on the African continent) and Antarctica. General Bathymetric Chart of the Oceans (GEBCO) bathymetry data were used (GEBCO Compilation Group, 2025). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Specifics and settings of the SoundTrap (ST) autonomous acoustic recorder used to collect the passive acoustic data. Factory calibration sensitivity value of the HTI-96-MIN (High Tech Inc.) hydrophone is provided.

Latitude (°S)	Longitude (°E)	Water depth (m)	ST depth (m)	Sample rate (kHz)	Sampling protocol (min h^{-1})	Duty cycle (%)	Hydrophone sensitivity (dB re 1 V/μPa)	Start recording date (dd/mm/yyyy)	End recording date (dd/mm/yyyy)
46.77	37.91	167	162	96	14	23	−165	April 26, 2021	May 06, 2022
46.77	37.91	165	160	96	14	23	−165	May 09, 2022	April 26, 2023

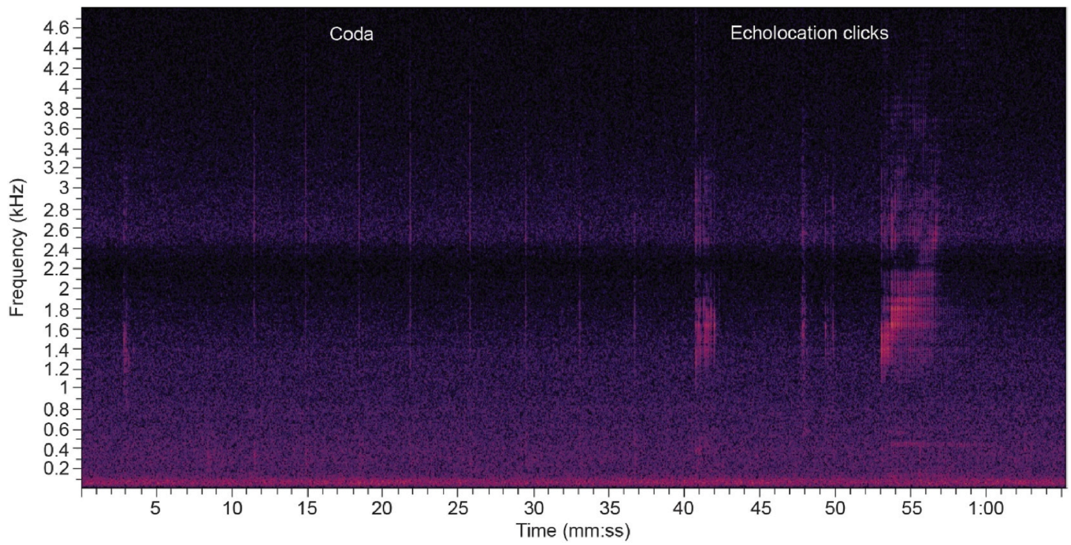

Fig. 2. Sperm whale clicks (eight-click coda and echolocation clicks) detected around the Prince Edward Islands (PEIs). Spectrogram parameters: 90 % overlap, Hann window, discrete Fourier transform (DFT) size of 2048 samples and window frame size of 0.145 s.

reviewed aurally using Sony WH-CH700N wireless noise cancelling headphones. Decimated acoustic data were analysed up to 4.8 kHz to detect sperm whale clicks (Fig. 2) while allowing for sperm whale clicks to be differentiated from clicks of killer whales (*Orcinus orca*) that have peaks above 10–100 kHz (e.g. Au et al., 2004) and are sometimes produced with social calls (Shabangu et al., 2024a). Specifically, the presence of codas with 4 s interclick interval (Sharma et al., 2024) assisted with the attribution of clicks to sperm whales. Sperm whale clicks were not classified to types, but their presence was noted for acoustic occurrence determination. Southern right whale (*Eubalaena australis*) gunshot-like sounds (e.g. Shabangu et al., 2021, 2025b) were also found on this data set but could not be attributed to this species since these were detected as singlets and very seldom to confidently attribute them to a species and will not be reported on further in this study.

The acoustic occurrence of sperm whales was defined as the presence of clicks within a sampling session (i.e. 14 min per hour), which was used to represent the presence of whales during that hour. In turn, the presence of clicks per hour described the diel acoustic occurrence of whales. Information on the daylight regime at the PEIs were determined from the mooring location using the 'suncalc' package (Thieurmel and Elmarhraoui, 2022) in R. The same definitions of daytime, nautical twilight (dawn and dusk), and nighttime from Shabangu et al. (2024b) are applied in this study. The data in this study were parsed using austral seasons where December through February represented summer, March through May represented autumn, June through August represented winter, and September through October represented spring.

2.2. Linking calls to the environment and noise

To establish relationships and interactions between the acoustic occurrence of sperm whales around the PEIs and the environment, including oceanographic conditions and ambient noise (i.e. acoustic ecology), a random forest (RF) model and generalized linear model (GLM) were applied.

2.2.1. Environmental conditions around the PEIs

The ecology, ocean circulation and nutrient cycling around the PEIs are driven by the variability of sub-Antarctic and Antarctic Fronts as these islands are located within the Southern Ocean Polar Frontal Zone (Rintoul, 2011). The island mass effect also contributes to the productivity of the area around the PEIs (Lamont and Toolsee, 2022). Satellite-derived and reanalysis oceanographic data on sea surface temperature (SST; °C), sea surface height (SSH; m), chlorophyll-a (mg m^{-3}), and wind speed (m s^{-1}) from Shabangu et al. (2024b) for the same period as this study were used to define the environmental conditions around the PEIs. Shabangu et al. (2024b) used a 2° × 2° (222 × 156 km) quadrant centred over the mooring location to extract these data based on previous research that found a good correlation between satellite-derived and *in situ* data. Shabangu et al. (2021) estimated sperm whale clicks off the west coast of South Africa to have a maximum detection of 83 km, which falls within the 2° × 2° quadrant. Giorli and Pinkerton (2023) considered 30 km (with a maximum of 80 km) to be a more realistic range for their study site in the Ross Sea, which is also within the above quadrant. SST was applied in this study as a proxy for physical processes that influence primary biological productivity, SSH as an indication of ocean circulation, chlorophyll-a as an index of primary productivity and phytoplankton biomass, and wind speed as an indication of ocean state.

2.2.2. Underwater noise level

Underwater noise level data at the acoustic recorder location from Shabangu et al. (2025c) is used in this study for the period April 2021 to December 2022, and data from January to April 2023 was unusable due to internal electrical noise from the acoustic recorder. However, this noise did not impair the detection of the loud sperm whale clicks between January and April 2023. Shabangu et al. (2025c) estimated noise levels within the low (20–120 and 121–800 Hz), medium (801–25000 Hz) and high (25001–48000 Hz) frequency bands. Given the high correlation observed between frequency bands (Shabangu et al., 2022), the lowest (20–120 Hz) and highest (25001–48000 Hz) frequency bands were used to alleviate the correlation. Underwater noise levels were measured as equivalent continuous sound pressure level (dB re 1 μPa), which represented the average sound level over 14 min of each hour. Equivalent continuous sound pressure level is used here to represent the average unweighted sound pressure of a continuous time-varying signal from various sources (Shabangu et al., 2025c).

2.2.3. Fitting statistical models

The RF model (Breiman, 2001) was applied to investigate the relationship between sperm whale acoustic occurrence and predictor variables (month, hour, chlorophyll-a, SSH, SST and wind speed) over two years (April 2021 through April 2023). Shabangu et al. (2017, 2019) found RF models to perform better than generalized boosted regression models and generalized additive models at investigating the acoustic occurrence of whales. As a result, the RF modelling approach was preferred and used in this study. Shabangu et al. (2024b) found no or low multicollinearity between the above predictor variables, and, as a result, all predictor variables were used in this study without reservation. Following the big imbalance between the presence and absence of sperm whale clicks, four sample balancing methods were tested and compared with each other using the receiver operating characteristic area under the curve (ROC AUC) as a measure of model performance. The four sample balancing methods compared were 1) ADAptive SYNthetic (ADASYN; He et al., 2008), 2) downsampling (Nallamuthu, 2020), 3) Synthetic Minority Over-sampling TEchnique (SMOTE; Chawla et al., 2002), and 4) upsampling (Nallamuthu, 2020). The ROC AUC scores indicated that upsampling method had better performance than other methods (Table 2), and this method was used hereon. 70 % and 30 % of the balanced data was used to respectively test and train the RF model as detailed in Shabangu et al. (2024a, b). The R package 'randomForest' (Liaw and Wiener, 2002) was utilized to fit the RF model. Altmann et al. (2010) permutation method was applied to determine statistically significant important variables. Significantly important predictors were informative whereas non-significant predictors were non-informative predictors although these are still important ecologically.

Acoustic detectability of sperm whales at various noise levels in the low and high frequency bands from April 2021 to December 2022 were investigated using GLMs (Dobson, 1990). The acoustic detectability of whales is the probability of whale calls to be detected by the acoustic recorder under various noise levels, and this detectability is influenced by masking, changes in whale vocalizing behaviour and the distance of vocalizing whales to the acoustic recorder. GLMs were fitted using the 'tidymodels' package (Kuhn and Wickham, 2020) in R. Probability of detecting sperm whales at the recording location was quantified at different noise levels with a reference point of 0.5 at which this species' probability of detection would decrease or increase considerably. All sampling balancing methods were used for GLMs due to similar performances of these methods (Shabangu et al., 2022, 2025c).

Table 2
Performance metrics of random forest (RF) models with different sample balancing methods. ROC AUC is for Receiver Operating Characteristic Area Under the Curve. ROC AUC score closer to 1 represents an excellent performing model and score closer to 0 represents a poor performing model. Boldfaced ROC AUC value represents the chosen method.

Sample balancing method	ROC AUC score
ADASYN	0.904
Downsampling	0.663
SMOTE	0.904
Unbalanced	0.684
Upsampling	**0.918**

3. Results

3.1. Acoustic occurrence and environmental variability

Sperm whale clicks were detected throughout the recording period (in 697 out of 729 recording days and in 917 out of 4024 recorded acoustic data hours) with increased occurrence in February through August, and there were minor peaks in the rest of the remaining months (Fig. 3a). Codas, slow clicks, and echolocation clicks (Fig. 2) were detected from this acoustic data set. Whale acoustic occurrence and environmental variability are presented consecutively in Fig. 3 for easier comparison. SSTs above 6 °C were observed between January and April (mid-summer through mid-autumn) (Fig. 3b). SSH fluctuated between months with higher values in September 2021/2022 and January 2022 (Fig. 3b). High daily chlorophyll-a concentration was found between November and early January (late spring to mid-summer). There were plenty of daily wind speed fluctuations between months (Fig. 3c). Sperm whale diel acoustic occurrence was mostly low after sunrise but high from late afternoon to early morning (15:00 to 01:00), and this trend varied between months (Fig. 4).

3.2. Responses to environmental and noise variation

Chlorophyll-a between 0.49 and 0.6 mg m^{-3}, late afternoon through early morning (15:00–01:00), February through August, SSH between 0 and 0.08 m, SST at 6 and 7.6 °C and low wind speed (<8 m s^{-1}) had the highest influence on the acoustic occurrence of sperm whales (Fig. 5a). Wind speed was the most important predictor of sperm whale acoustic occurrence (Fig. 5b). Hour, SSH, chlorophyll-a and SST were moderate important predictors while month was the least important predictor of sperm whale acoustic occurrence (Fig. 5b). All predictor variables were significantly important, indicating that they are all informative predictors. The probability of detecting sperm whale acoustic occurrence decreased with the increase in the high frequency band (25001–48000 Hz) noise level (Fig. 5c). There were small changes in sperm whale detection probability with noise changes in the low (20–120 Hz) frequency band (Fig. 5c). Most of the probability of detecting sperm whales were below the 0.5 (50 %) reference level.

4. Discussion

This study provides the first description of sperm whale acoustic occurrence around the PEIs in relation to environmental conditions and variations in underwater noise. Sperm whales were acoustically present year-round, highlighting this area as an important habitat for this species and the vulnerability of this species to interaction with the fishery on its prey, Patagonian toothfish, operating within the PEIs' EEZ. Knowledge and understanding of this species' acoustic ecology will assist with the protection and management of this species relative to growing threats and changes in the ocean.

4.1. Acoustic presence around PEIs

Sperm whale clicks were detected year-round around the sub-Antarctic PEIs, reflecting this region as an important and useful habitat of this species. Based on the sub-Antarctic interpulse interval results of Miller et al. (2024), sperm whales detected here are likely males. Additionally, Best (2007) identified the sub-Antarctic area, including the PEIs, as one of the "male concentration areas in summer" in the Southern Ocean. The year-round presence of this species in this region is likely supported by the availability of enough prey resources to sustain them. For example, the Patagonian toothfish longline fishery around the PEIs operates throughout the year (December–November)

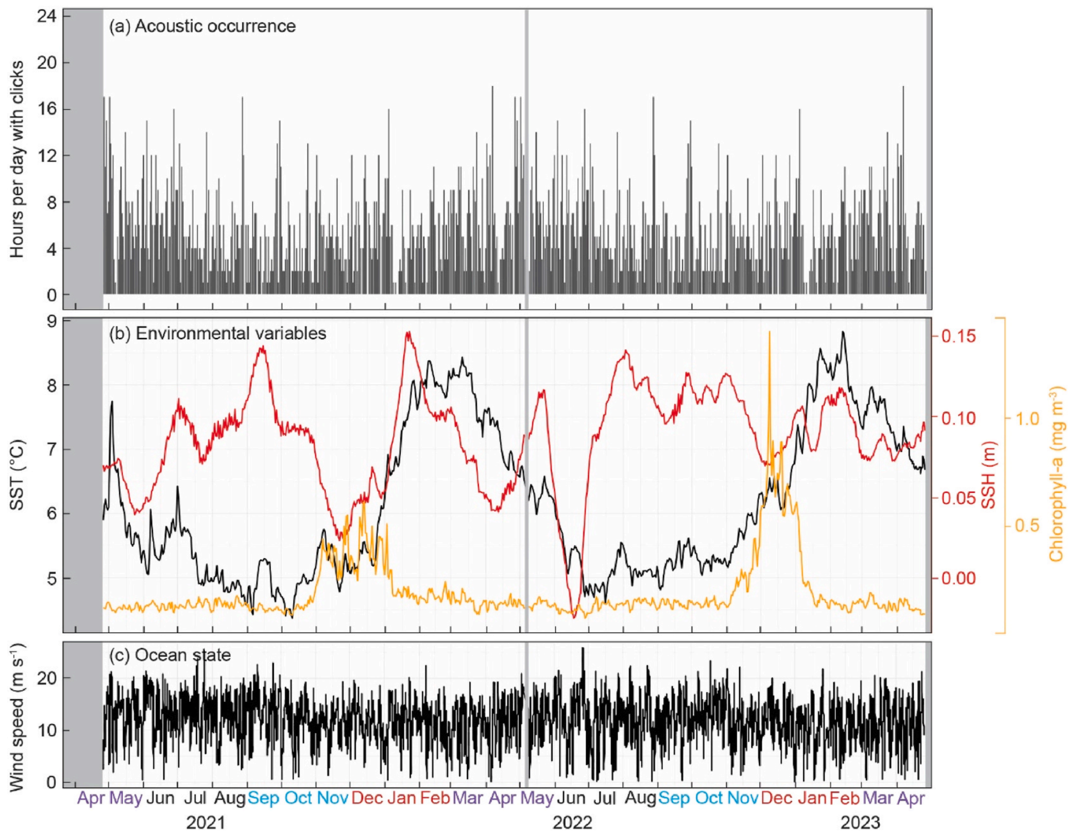

Fig. 3. (a) Number of hours per day with sperm whale clicks and (b, c) daily trends of environmental conditions around the Prince Edward Islands (PEIs). Grey shaded areas signify periods without passive acoustic monitoring effort. Font colour of month denotes the season of each month where purple is for autumn, black is for winter, light blue is for spring, and red is for summer. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

given the availability and abundance of fish (Brandão and Butterworth, 2021). This year-round presence also corroborates results from the Ross Sea in the Southern Ocean (Giorli and Pinkerton, 2023). Tixier et al. (2020) estimated from fishery reported marine mammal surfacing cues that killer whales were more responsible for depredating Patagonian toothfish longlines around the PEIs than sperm whales; however, the results of this study show more acoustic presence of sperm whales than killer whales from Shabangu et al. (2024a). If these two cetacean species are always echolocating while foraging, then these results might necessitate the revisitation of the amount of fish removed from the longline fishery by these marine mammals. Sperm whale clicks have a longer maximum detection range (~80 km) than killer whales (~10 km), which would have increased their probability of detection. Given the long-term presence of sperm whales around the PEIs, the nutritional needs of this species should be considered in the fisheries management plans of this area and the whole Southern Ocean.

The highest detection of sperm whale clicks around the PEIs was in February through August, which might indicate the transition of whales through the PEIs from Antarctica to the low latitudes. For example, Best (1969) observed an increased presence of Antarctic diatom film on the skins of medium-sized and large males off the west coast of South Africa between February and July as a sign of whale arrival from Antarctica. Moreover, this increased sperm whale detection corresponds to the acoustic presence of other whales such as blue, fin and humpback whales (Shabangu et al., 2024b). Off the sub-Antarctic Heard Island, Miller et al. (2024) detected sperm whale clicks intermittently between September and January but more continuously in February and March, which also corroborates whale movement to the low latitudes. On the other hand, Shabangu et al. (2024c) detected sperm whale clicks in December through February in the Eastern Antarctic (0–180 °E). Sperm whales were detected year-round in the Ross Sea, Southern Ocean, with high click detections in October through April (Giorli and Pinkerton, 2023). Off the west coast of South Africa, sperm whales were acoustically present year-round with two high occurrences in February and August through October (Shabangu and Andrew, 2020). The above regional difference in the occurrence of sperm whales might be due to the movement and migration of these whales and different habitat occupancy. Detection of sperm whale clicks at the water depth of approximately 160 m might have been enabled by the long-range propagation (maximum of ~80 km) of sperm whale clicks relative to the wide varying bathymetry around the PEIs, or an indication that these whales can occupy or venture into water depths shallower than 200 m.

The high late afternoon and nighttime hours diel vocalizing pattern of sperm whales around the PEIs led to the strong influence of these hours on the RF model sperm whale acoustic occurrence with nighttime hours having the highest impact. This observed behaviour might be associated with the diel vertical migration of this species' prey, mostly deep-sea cephalopods and fish. This dominant nighttime acoustic presence is different to the more daytime vocalization observed by previous studies in the Southern Hemisphere (Miller and Miller, 2018; Shabangu and Andrew, 2020; Giorli and Pinkerton, 2023). The more nighttime acoustic vocalization might be to avoid detection by and competition with killer whales that vocalized more during the day around the PEIs (Shabangu et al., 2024a) as sperm whales have been found to respond negatively to sounds of predatory killer whales (Miller et al., 2022). The acoustic occurrence of sperm whales observed in this study is different from that of killer whales reported by Shabangu et al. (2024a), further validating the classification of these clicks to sperm whales. Eight-click codas detected here (Fig. 2) are similar to those detected from April through December in Mauritius, southwestern Indian Ocean (Huijser

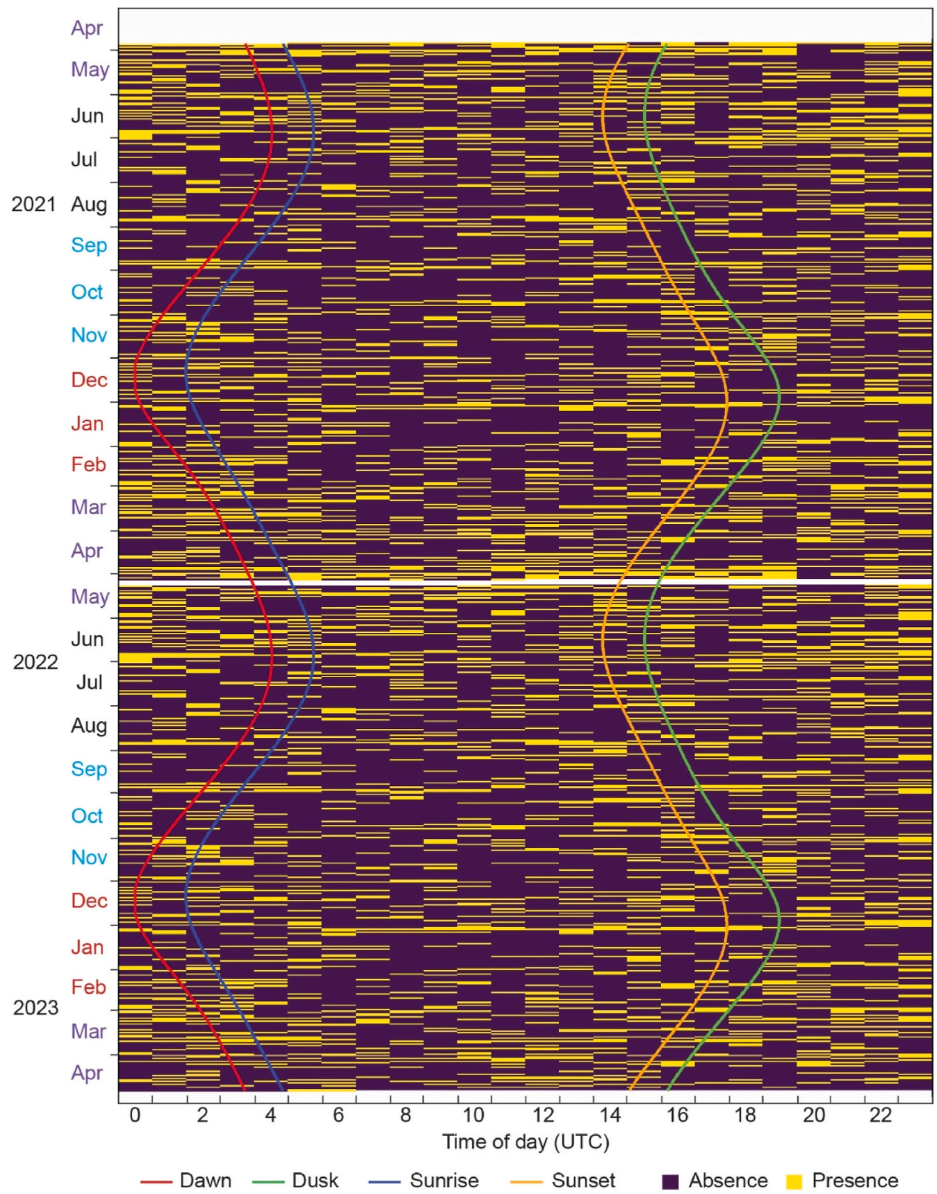

Fig. 4. Diel acoustic occurrence of sperm whales over different months during the study period. White shaded areas represent periods without passive acoustic monitoring effort. Month font colours represent seasons: red = summer, purple = autumn, black = winter, and blue = spring. Universal Coordinated Time (UTC) is used. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

et al., 2020), which might indicate movement of animals between these locations and/or similar vocal social structure. A detailed acoustic research on the social structure and demography (through interpulse interval measurements) of whales around the PEIs is recommended in the future.

4.2. Acoustic ecology of sperm whales

Sperm whale acoustic occurrence was highly influenced by wind speed, indicating the strong influence of this variable on the physics of call propagation and the ecology of the species. Off the west coast of South Africa, diel and seasonal cycle changes were more important than environmental variation in predicting sperm whale vocal activity (Shabangu and Andrew, 2020). This difference in the key predictors of acoustic occurrence suggests that this species may exhibit region-specific acoustic adaptations. Killer whale acoustic occurrence around the PEIs was also highly predicted by wind speed (Shabangu et al., 2024a). In contrast, the occurrence of baleen whales was highly predicted by month and SST (Shabangu et al., 2024b). This wind speed influence on toothed cetaceans might be due to their high frequency calls being easily attenuated by wind-induced sea surface air bubbles and masked by wind-induced noise (Lurton, 2002; Shabangu et al., 2014, 2022, 2025c). Future climate-driven changes in wind speed will definitely affect this species acoustic ecology. Productivity-related predictor variables such as SSH, chlorophyll-a and SST had similar moderate variable importance on sperm whale occurrence, which further cements the dominance of wind speed in predicting this species' acoustic occurrence. Seasonal cycle changes captured by month were the least important predictor of sperm whale occurrence since whale calls were present throughout the year and were least influenced by seasonality.

The probability of detecting sperm whales decreased with the increase in high frequency band noise level but showed little response to low frequency band noise change, which suggests that the high frequency noise predicted by iceberg volume (Shabangu et al., 2025c) affected the propagation of their calls. On the contrary, sperm whale acoustic detectability off the west coast of South Africa responded to

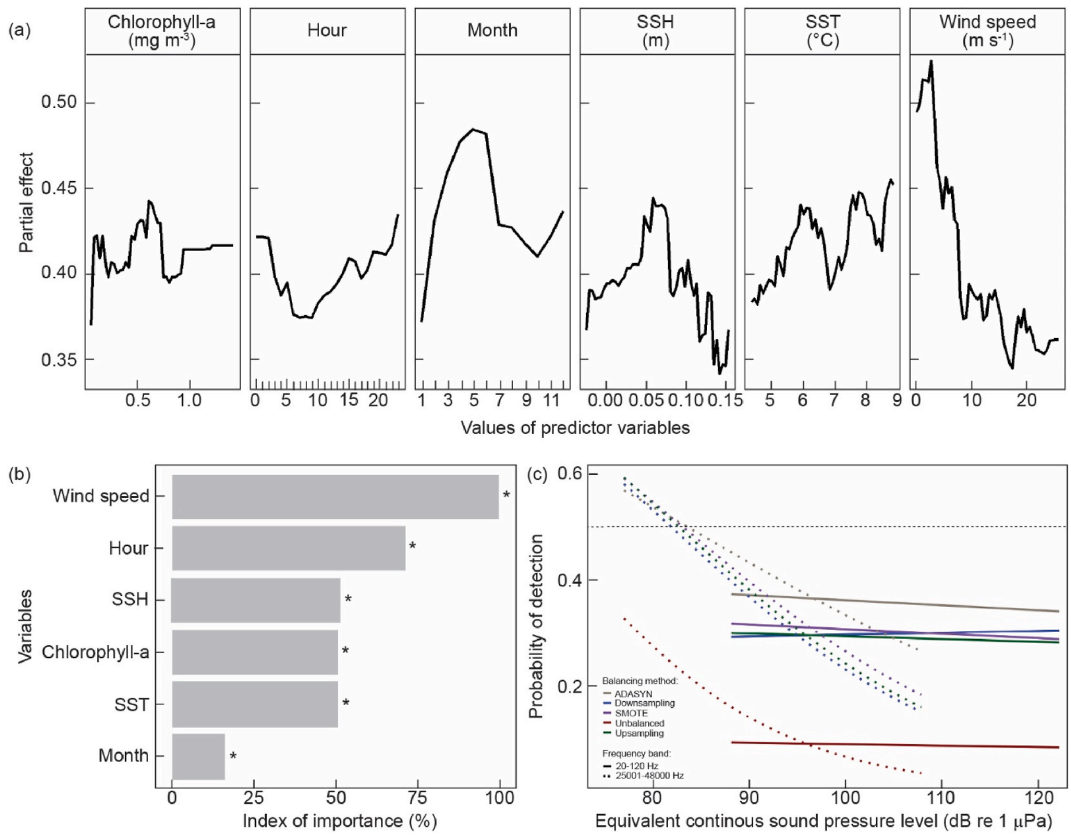

Fig. 5. (a) Partial effects and (b) ranked importance of predictor variables based on random forest (RF) model using the upsampling method. (c) Generalized linear model (GLM) dose-response curves of ambient equivalent continuous sound pressure level partial effect on the probability of detecting sperm whales at the low (continuous lines) and high (dashed lines) frequency band based on different sample balancing methods. Asterisks (*) signify statistically significant ($p < 0.05$) importance of variables, and NS signifies non-significant ($p > 0.05$) importance of variables. The dashed horizontal line at 0.5 demarcates the 50 % point for acoustic detection of sperm whales at a given noise level.

both low and high frequency bands in the presence of vessel traffic (Shabangu et al., 2022). As off the west coast of South Africa, most of the probability of detecting sperm whales at the PEIs was below 50 %, indicating the high influence of underwater noise on this species' acoustic ecology.

5. Conclusion

Sperm whales were present acoustically for the whole study period with their presence mainly predicted by changes in wind speed. The peak in sperm whale acoustic occurrence corresponds to the northward migration of whales to the low latitudes, indicating that whales are transiting through this area. Acoustic detectability of whales was not influenced by low frequency band noise in the absence of vessel traffic but by high frequency band that corresponds to their vocalizing frequency and noise dominated by iceberg volume. Whales vocalized more from late afternoon to early morning with some minor seasonal variations, and whales detected here are possibly males based on their distribution. The detection of sperm whale echolocation clicks in this study suggests that these whales may be feeding around the PEIs and are involved in the depredation of Patagonian toothfish longline fishery catches. Sperm whales are the eighth cetacean species to be detected around the PEIs, which underscores and emphasises this region as a productive and high-diversity habitat for cetaceans in the Southern Ocean. Future management and conservation strategies of the PEIs should consider and include the ecological importance and needs of this species. Lastly, passive acoustic monitoring reveals the consistent presence of another marine mammal species that is rarely sighted in the vicinity of the PEIs.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

Altmann, A., Tolos, L., Sander, O., Lengauer, T., 2010. Permutation importance: a corrected feature importance measure. Bioinform 26 (10), 1340–1347. https://doi.org/10.1093/bioinformatics/btq134.

André, M., Caballé, A., van der Schaar, M., et al., 2017. Sperm whale long-range echolocation sounds revealed by ANTARES, a deep-sea neutrino telescope. Sci. Rep. 7, 45517. https://doi.org/10.1038/srep45517.

Au, W.W.L., Ford, J.K.B., Horne, J.K., Newman Allman, K.A., 2004. Echolocation signals of free-ranging killer whales (*Orcinus orca*) and modeling of foraging for chinook salmon (*Oncorhynchus tshawytscha*). J. Acoust. Soc. Am. 115 (2), 901–909. https://doi.org/10.1121/1.1642628.

Best, P.B., 1969. The sperm whale (*Physeter catodon*) off the west coast of South Africa 4. Distribution and movements. S. A.fr. Div. Sea. Fish. Invest. Rep. 78, 1–12.

Best, P.B., 1979. Social organization in sperm whales, Physeter macrocephalus. In: Winn, H.E., Olla, B.L. (Eds.), Behavior of Marine Animals. Springer, Boston, MA. https://doi.org/10.1007/978-1-4684-2985-5_7.

Best, P.B., 2007. Whales and Dolphins of the Southern African Subregion. Cambridge University Press, Cambridge.

Brandão, A., Butterworth, D., 2021. The 2020 Operational Management Procedure for the Toothfish (*Dissostichus eleginoides*) Resource in the Prince Edward Islands Vicinity. FISHERIES/2021/JUN/SWG-DEM/09. Department of Forestry, Fisheries and the Environment, Cape Town. https://doi.org/10.25375/uct.16455189.v1. (Accessed 16 August 2025).

Breiman, L., 2001. Random forests. Mach. Learn. 45, 5–32. https://doi.org/10.1023/A:1010933404324.

Chawla, N.V., Bowyer, K.W., Hall, L.O., Kegelmeyer, W.P., 2002. SMOTE: synthetic minority over-sampling technique. J. Artif. Intell. Res. 16, 321–357. https://doi.org/10.48550/arXiv.1106.1813.

Dobson, A.J., 1990. An Introduction to Generalized Linear Models. Chapman and Hall, London.

GEBCO Compilation Group, 2025. GEBCO 2025 Grid. https://doi.org/10.5285/37c52e96-24ea-67ce-e063-7086abc05f29. (Accessed 1 October 2025).

Giorli, G., Goetz, K.T., 2020. Acoustically estimated size distribution of sperm whales (*Physeter macrocephalus*) off the East Coast of New Zealand. N. Z. J. Mar. Freshw. Res. 54 (2), 177–188. https://doi.org/10.1080/00288330.2019.1679843.

Giorli, G., Pinkerton, M.H., 2023. Sperm whales forage year-round in the ross sea region. Front. Remote Sens. 4, 940627. https://doi.org/10.3389/frsen.2023.940627.

He, H., Bai, Y., Garcia, E.A., Li, S., 2008. ADASYN: adaptive synthetic sampling approach for imbalanced learning. In: Proceedings of the 2008 IEEE International Joint Conference on Neural Networks(IEEE World Congress on Computational Intelligence), pp. 1322–1328. https://doi.org/10.1109/IJCNN.2008.4633969. Hong Kong.

Huijser, L.A.E., Estrade, V., Webster, I., Mouysset, L., Cadinouche, A., Dulau-Drouot, V., 2020. Vocal repertoires and insights into social structure of sperm whales (*Physeter macrocephalus*) in Mauritius, southwestern Indian Ocean. Mar. Mamm. Sci. 36, 638–657. https://doi.org/10.1111/mms.12673.

Jaquet, N., Dawson, S., Douglas, L., 2001. Vocal behavior of male sperm whales: why do they click? J. Acoust. Soc. Am. 109 (5), 2254–2259. https://doi.org/10.1121/1.1360718.

K. Lisa Yang Center for Conservation Bioacoustics, 2025. Raven Pro: Interactive Sound Analysis Software. The Cornell Lab of Ornithology, Ithaca, NY (Version 1.6.5) [Computer software]. Available from. https://ravensoundsoftware.com/.

Kuhn, M., Wickham, H., 2020. Tidymodels: a collection of packages for modeling and machine learning using tidyverse principles. https://www.tidymodels.org.

Lamont, T., Toolsee, T., 2022. Spatial and seasonal variations of the island mass effect at the sub-Antarctic Prince edward Islands archipelago. Remote Sens. 14, 2140. https://doi.org/10.3390/rs14092140.

Liaw, A., Wiener, M., 2002. Classification and regression by randomForest. R. News 2 (3), 18–22.

Lombard, A.T., Reyers, B., Schonegevel, L.Y., et al., 2007. Conserving pattern and process in the Southern Ocean: designing a marine protected area for the Prince Edward Islands. Antarct. Sci. 19 (1), 39–54. https://doi.org/10.1017/S0954102007000077.

Lurton, X., 2002. An Introduction to Underwater Acoustics: Principles and Applications. Springer, London.

Madsen, P.T., Wahlberg, M., Møhl, B., 2002. Male sperm whale (*Physeter macrocephalus*) acoustics in a high-latitude habitat: implications for echolocation and communication. Behav. Ecol. Sociobiol. 53, 31–41. https://doi.org/10.1007/s00265-002-0548-1.

Matthews, L.H., 1938. The sperm whale, *Physeter catodon*. Discov. Rep. 17, 93–168.

Miller, B.S., Miller, E.J., 2018. The seasonal occupancy and diel behaviour of Antarctic sperm whales revealed by acoustic monitoring. Sci. Rep. 8, 5429. https://doi.org/10.1038/s41598-018-23752-1.

Miller, P.J.O., Isojunno, S., Siegal, E., Lam, F.A., Kvadsheim, P.H., Curé, C., 2022. Behavioral responses to predatory sounds predict sensitivity of cetaceans to anthropogenic noise within a soundscape of fear. Proc. Natl. Acad. Sci. USA 119 (13), e2114932119. https://doi.org/10.1073/pnas.2114932119.

Miller, B.S., Masere, C., Milnes, M., Cleeland, J., Lamb, T., Maschette, D., Welsford, D., 2024. Heard off heard: acoustic detections of sperm whales (*Physeter macrocephalus*) and other cetaceans off heard Island. JASA Express Lett. 4 (6), 061201. https://doi.org/10.1121/10.0026242.

Nallamuthu, N., 2020. Handling imbalanced data – machine learning, computer vision and NLP. https://www.analyticsvidhya.com/blog/2020/11/handling-imbalanced-data-machine-learning-computer-vision-and-nlp/. (Accessed 11 August 2025).

Oliveira, C., Wahlberg, M., Silva, M.A., Johnson, M., et al., 2016. Sperm whale codas may encode individuality as well as clan identity. J. Acoust. Soc. Am. 139, 2860–2869. https://doi.org/10.1121/1.4949478.

Pöyhönen, V., Thomisch, K., Kovacs, K.M., et al., 2024. High Arctic "hotspots" for sperm whales (*Physeter macrocephalus*) off western and northern Svalbard, Norway, revealed by multi-year Passive acoustic monitoring (PAM). Sci. Rep. 14, 5825. https://doi.org/10.1038/s41598-024-56287-9.

R Core Team, 2024. R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Reisinger, R.R., Raymond, B., Hindell, M.A., et al., 2018. Habitat modelling of tracking data from multiple marine predators identifies important areas in the Southern Indian Ocean. Divers. Distrib. 24, 535–550. https://doi.org/10.1111/ddi.12702.

Rendell, L.E., Whitehead, H., 2003. Vocal clans in sperm whales (*Physeter macrocephalus*). Proc. R. Soc. Lond. Ser. B 270, 225–231.

Rintoul, S.R., 2011. Antarctic circumpolar current. In: Steele, J.H., Thorpe, S.A., Turekian, K.K. (Eds.), Encyclopedia of Ocean Sciences, second ed., 4. Academic Press, London, UK, pp. 178–190.

Sakai, T., 2024. PAMmisc: miscellaneous functions for passive acoustic analysis. R Package Version 1.12.1. https://CRAN.R-project.org/package=PAMmisc.

Shabangu, F.W., Andrew, R.K., 2020. Clicking throughout the year: sperm whale clicks in relation to environmental conditions off the west coast of South Africa. Endanger. Species Res. 43, 475–494. https://doi.org/10.3354/esr01089.

Shabangu, F.W., Ona, E., Yemane, D., 2014. Measurements of acoustic attenuation at 38 kHz by wind-induced air bubbles with suggested correction factors for hull-mounted transducers. Fish. Res. 151, 47–56. https://doi.org/10.1016/j.fishres.2013.12.008.

Shabangu, F.W., Yemane, D., Stafford, K.M., Ensor, P., Findlay, K.P., 2017. Modelling the effects of environmental conditions on the acoustic occurrence and behaviour of Antarctic blue whales. PLoS One 12, e0172705. https://doi.org/10.1371/journal.pone.0172705.

Shabangu, F.W., Findlay, K.P., Yemane, D., Stafford, K.M., van den Berg, M., Blows, B., Andrew, R.K., 2019. Seasonal occurrence and diel calling behaviour of Antarctic blue whales and fin whales in relation to environmental conditions off the west coast of South Africa. J. Mar. Syst. 190, 25–39. https://doi.org/10.1016/j.jmarsys.2018.11.002.

Shabangu, F.W., Andrew, R.K., Findlay, K., 2021. Acoustic occurrence, diel-vocalizing pattern and detection ranges of southern right whale gunshot sounds off South Africa's west coast. Mar. Mamm. Sci. 37, 733–750. https://doi.org/10.1111/mms.

Shabangu, F.W., Yemane, D., Best, G., Estabrook, B.J., 2022. Acoustic detectability of whales amidst underwater noise off the west coast of South Africa. Mar. Pollut. Bull. 184, 114122. https://doi.org/10.1016/j.marpolbul.2022.114122.

Shabangu, F.W., Daniels, R., Jordaan, R.K., de Bruyn, P.J.N., van den Berg, M.A., Lamont, T., 2024a. Killer whale acoustic patterns respond to prey abundance and environmental variability around the Prince Edward Islands, Southern Ocean. R. Soc. Open Sci. 10, 230903. https://doi.org/10.1098/rsos.230903.

Shabangu, F.W., Munoz, T., Van Uffelen, L., et al., 2024b. Diverse baleen whale acoustic occurrence around two sub-antarctic Islands: a tale of residents and visitors. Sci. Rep. 14, 21663. https://doi.org/10.1038/s41598-024-72696-2.

Shabangu, F.W., Stafford, K.M., Findlay, K.P., et al., 2024c. Overview of the IWC SOWER cruise circumpolar acoustic survey data and analyses of Antarctic blue whale calls. J. Cetacean Res. Manage., Spec. (4), 21–41. https://doi.org/10.47536/jcrm.v4i1.1040.

Shabangu, F.W., van der Heever, G., von den Meden, G., Truter, H., Lamberth, S., Gon, O., 2025a. In review. Rhyming in the cold: first evidence of soniferous fishes in the Southern Ocean. Remote Sens. Ecol. Conserv.

Shabangu, F.W., Hlati, K., van den Berg, M.A., Lamont, T., Kirkman, S.P., 2025b. Monthly and diel acoustic occurrence of four baleen whale species in South African waters. Ecol. Evol. 15 (8), e72004. https://doi.org/10.1002/ece3.72004.

Shabangu, F.W., Yemane, D., Stander, N., Estabrook, B.J., 2025c. Underwater soundscape indicates low anthropogenic influence around two sub-antarctic islands. R. Soc. Open Sci. 12, 250677. https://doi.org/10.1098/rsos.250677.

Sharma, P., Gero, S., Payne, R., et al., 2024. Contextual and combinatorial structure in sperm whale vocalisations. Nat. Commun. 15, 3617. https://doi.org/10.1038/s41467-024-47221-8.

Thieurmel, B., Elmarhraoui, A., 2022. Suncalc: compute sun position, sunlight phases, moon position and lunar phase. R Package Version 0.5.1. https://CRAN.R-project.org/package=suncalc.

Tixier, P., Burch, P., Massiot-Granier, F., et al., 2020. Assessing the impact of toothed whale depredation on socio-ecosystems and fishery management in wide-ranging subantarctic fisheries. Rev. Fish Biol. Fish. 30, 203–217. https://doi.org/10.1007/s11160-020-09597-w.

Watkins, W.A., Schevill, W.E., 1977. Sperm whale codas. J. Acoust. Soc. Am. 62, 1485–1490. https://doi.org/10.1121/1.381678.

Westell, A., Rowell, T.J., Posdaljian, N., Solsona-Berga, A., Van Parijs, S.M., DeAngelis, A.I., 2024. Acoustic presence and demographics of sperm whales (*Physeter macrocephalus*) off southern New England and near a US offshore wind energy area. ICES J. Mar. Sci. 82 (4). https://doi.org/10.1093/icesjms/fsae012 fsae012.

Whitehead, H., 1996. Babysitting, dive synchrony, and indications of alloparental care in sperm whales. Behav. Ecol. Sociobiol. 38, 237–244. https://doi.org/10.1007/s002650050238.

Whitehead, H., 2024. Sperm whale clans and human societies. R. Soc. Open Sci. 11, 231353. https://doi.org/10.1098/rsos.231353.

Whitehead, H., Rendell, L., 2004. Movements, habitat use and feeding success of cultural clans of South Pacific sperm whales. J. Anim. Ecol. 73, 190–196. https://doi.org/10.1111/j.1365-2656.2004.00798.x.