doi:10.26443/seismica.v3i2.1153

SEISMICA

Spatiotemporal Variability of Fin Whale and Blue Whale Calls Detected by Land Seismometers Along the Lower St. Lawrence Seaway

Eva Goblot * [1], **Yajing Liu** [1], **Alexandre Plourde** [2], **Pierre Cauchy** [3], **Jeanne Mérindol** [3], **Coralie Bernier-Breton** [3], **Ge Li** [4], **Basile Roth** [4]

[1]Department of Earth and Planetary Sciences, McGill University, Montréal, Canada, [2]Natural Resources Canada, Geological Survey of Canada Atlantic, Dartmouth, Canada, [3]Institut des sciences de la mer (ISMER), Université du Québec à Rimouski (UQAR), Rimouski, Canada, [4]Mila - Québec Artificial Intelligence Institute, Montréal, Canada

Author contributions: *Conceptualization*: Eva Goblot, Yajing Liu, Alexandre Plourde, Pierre Cauchy. *Software*: Alexandre Plourde, Ge Li, Basile Roth. *Formal Analysis*: Eva Goblot, Ge Li, Basile Roth. *Writing - Original Draft*: Eva Goblot, Yajing Liu, Ge Li, Basile Roth. *Writing - Review & Editing*: Eva Goblot, Yajing Liu, Alexandre Plourde, Pierre Cauchy, Jeanne Mérindol, Coralie Bernier, Ge Li, Basile Roth. *Visualization*: Eva Goblot, Yajing Liu.

Abstract The Lower St. Lawrence Seaway (LSLS) is critical to Canada's economy both as part of a major marine shipping corridor and a site of intensive fishing. Every year, fin whales and blue whales frequent the LSLS feeding ground. Understanding the mechanisms driving whale habitat usage is key for making informed decisions on shipping and fishing, reducing whale collision risks and mitigating noise pollution. We detect whales in the LSLS with land seismometers by using a method that relies on the intervals of the regularly repeating low-frequency calls. The resulting catalogue contains 14 076 fin whale detections and 3739 blue whale detections between February 2020 and January 2022. These detections follow the overall pattern of hydrophones, with most detections from fall to early winter in the Estuary and until mid-winter/spring in the Gulf. High detection rates in the Northwest Gulf throughout the winter months demonstrate that this region is potentially utilized year-round. This labelled catalogue may be suitable for developing a deep learning-based whale call detection algorithm. Making use of seismic data and deep learning can increase whale monitoring coverage within the LSLS and elsewhere.

Production Editor:
Gareth Funning
Handling Editor:
Stephen Hicks
Copy & Layout Editor:
Abhineet Gupta

Signed reviewer(s):
Alex Saoulis

Received:
November 15, 2023
Accepted:
July 30, 2024
Published:
September 16, 2024

1 Introduction

The Northwest Atlantic fin whale (*Balaenoptera physalus*) and blue whale (*Balaenoptera musculus*) populations have been shown to frequent the Lower St. Lawrence Seaway (LSLS) each year for foraging. Oceanic processes in the Gulf and the Estuary create regions of high biological productivity, with the head of the Laurentian Channel being the most active region for marine mammals in the LSLS (Simard and Roy, 2018). The Northwest Atlantic blue whale was listed as endangered under the Species at Risk Act in 2005, and the Northwest Atlantic fin whale was designated a special concern status in 2005 by the Committee on the Status of Endangered Wildlife in Canada, due to the reduction in population sizes by whaling in the 20th century and modern threats including collision with marine traffic and entanglement in fishing gear (Ramp et al., 2021). As such, a better understanding of the spatial and temporal distribution of marine mammals in the LSLS is needed to inform conservation policies.

Traditionally, whales have been monitored by conducting visual surveys using photo-identification (Ramp and Sears, 2012; Ramp et al., 2015). This method is difficult because it is limited by weather conditions, and costly to conduct (Stafford et al., 2007). Recent remote sensing initiatives using high-resolution satellite imagery may greatly increase the spatial coverage at near-real-time for critically endangered whale species such as the North Atlantic Right Whales (Hodul et al., 2023). Whales produce many acoustic signals often associated with either social or foraging functions (Romagosa et al., 2021). Northwest Atlantic fin whales produce songs consisting of a series of individual call units ranging in frequency from 18–21 Hz, lasting 1 s, and repeated every 10–15 s (Roy et al., 2018). The interval between consecutive call units is referred to as the inter-note interval (INI). Similarly, Northwest Atlantic blue whales also produce songs consisting of a series of individual tonal A-call units, at slightly lower frequencies ranging from 16–18 Hz, lasting approximately 8 s, with an INI of 68–78 s (Mellinger and Clark, 2003). In some cases, a secondary B-call is produced following the A-call (Simard et al., 2016). These songs with stereotyped repetition are believed to act as social/mating

*Corresponding author: eva.goblot@dal.ca

displays that are only produced by males (Romagosa et al., 2024; Širović and Oleson, 2022). In addition, fin whales and blue whales produce intermittent audible 40 Hz calls downsweeping from 75–40 Hz and D-calls from 90–25 Hz, respectively, on feeding grounds (Simard et al., 2016; Romagosa et al., 2021; Širović and Oleson, 2022). The INI and frequency range of whale songs are distinctive characteristics that vary spatially and are used to differentiate stocks and populations (Romagosa et al., 2024). Moreover, acoustic recordings from hydrophones deployed in the water have allowed biologists to better understand geographic ranges of whale populations and their habitat usage (Watkins et al., 2000; Stafford et al., 2007). Hydrophone recordings along the LSLS have provided a rich database of whale activities (Simard et al., 2016; Roy et al., 2018). Hydrophone monitoring demonstrated that blue whales and fin whales were present year-round from 2010–2016 (Simard et al., 2016) and from 2010–2017 (Roy et al., 2018) in the Southern Gulf of St. Lawrence, respectively. However, the hydrophone whale call catalogues are often hindered by the spatial (suitable location) and temporal (ice-free season) limitations of the hydrophone deployment; observations outside the summer and fall months are often sporadic and limited (Roy et al., 2018). Questions remain about where exactly Northwest Atlantic whale species go over the winter, as well as the timing of migration. Previous studies have suggested that the type of migration in and out of the St. Lawrence Gulf and Estuary may be complex: it is unknown whether these fin whale and blue whale populations complete a full migration with a predictable, round-trip movement of the entire population, or a partial migration where only a fraction of the population departs, as sea ice accumulates over the winter (Lesage et al., 2017). Therefore, long term year-round monitoring in widespread locations is necessary to better understand the seasonal patterns of baleen whale habitat usage throughout the LSLS.

Many bioacoustic studies apply automated whale detection methods such as energy detectors (Širović et al., 2015; Pilkington et al., 2018), spectrogram correlation (Mellinger and Clark, 2000), or matched filtering (Stafford et al., 1998; Weirathmueller et al., 2017), to increase the efficiency in identifying highly stereotyped signals in large passive acoustic monitoring (PAM) datasets. Over the last 20 years, seismic recording devices have been increasingly used as a complementary tool to monitor marine mammals. Fin whales and blue whales vocalize powerful ground-shaking low-frequency calls, comparable to source levels produced by ship noise (Kuna and Náb ělek, 2021). The average source level of fin whale and blue whale calls is around 189 dB (re 1 µPa at 1 m) over 15–28 Hz and 25–29 Hz, respectively, in the Southern Ocean (Širović et al., 2007). Several studies have successfully used ocean bottom seismometer (OBS) networks to detect whale calls and/or track whales globally (Dunn and Hernandez, 2009; Wilcock, 2012; Kuna and Nábělek, 2021; Franek et al., 2017; Matias and Harris, 2015; Bouffaut et al., 2020; Dréo et al., 2019; Tary et al., 2024; Ryoichi, 2015; Brodie and Dunn, 2015). A first study using distributed acoustic sensing (DAS) to monitor cetaceans in the Arctic demonstrates the potential of DAS to provide real-time monitoring over large spatial scales (tens of kilometers) with a spatial resolution of only a few meters and finds diverse baleen whale call vocalizations along the fiber optic cable (Bouffaut et al., 2022). Recently, machine learning methods, particularly deep learning (DL) based algorithms, have been explored for the detection of various whale vocalizations, including non-stereotyped fin whale 40 Hz and blue whale D-calls (Rasmussen and Širović, 2021) and fin whale songs under variable signal context (Madhusudhana et al., 2021). DL-based algorithms can further improve acoustic monitoring, with sufficient annotated datasets for training and evaluation.

As the sound sources (whales) come closer to the shorelines, their sound waves can travel across the water/sediment/bedrock layers to be recorded even at land seismometers, as recently demonstrated in the LSLS (Plourde and Nedimović, 2022). Since these land seismometers operate continuously and record ground shaking up to 100 Hz, they can complement traditional whale monitoring methods such as hydrophone datasets and visual surveys, by providing year-round monitoring of low-frequency fin whale and blue whale calls, and identification of coastal whale aggregation regions. In this study we build upon the first land seismometer detection catalogue of fin whales and blue whales in the LSLS (October 2015 to February 2020), by analyzing daily seismic waveform data from February 2020 to January 2022, using a method that relies on the characteristic recurrence intervals of the regularly repeating low-frequency whale calls developed by Plourde and Nedimović (2022). Based on the distribution of whale calls recorded by the seismometers, we discuss spatial and temporal variations, including multi-year trends. A sub-sample of detections from a land seismometer are compared to whale calls collected from a hydrophone close to the seismometer. Finally, we discuss how the rich catalogue prepared in this study can support the development of a deep learning-based algorithm for whale call detection with potential applications to OBS datasets in the LSLS and other regions.

2 Data and Methods

2.1 Data Collection

The St. Lawrence River begins as the freshwater outflow from the Great Lakes (Ontario). The region downstream of Ile d'Orléans is known as the St. Lawrence Estuary and is where the upstream freshwater begins to mix with North Atlantic Ocean. Pointe-des-Monts marks the major opening of the waterway, separating the Estuary from the Gulf (Fig. 1). Since whales are often observed as far upstream as the Saguenay Fjord in the Estuary, we use the available broadband land seismometers between the Saguenay Fjord and the Gulf of St. Lawrence.

Daily seismic waveform data from February 2020 to January 2022 were retrieved from the IRIS DMC database, under the Canadian National Seismograph Network (CN) for six land seismometers in the LSLS:

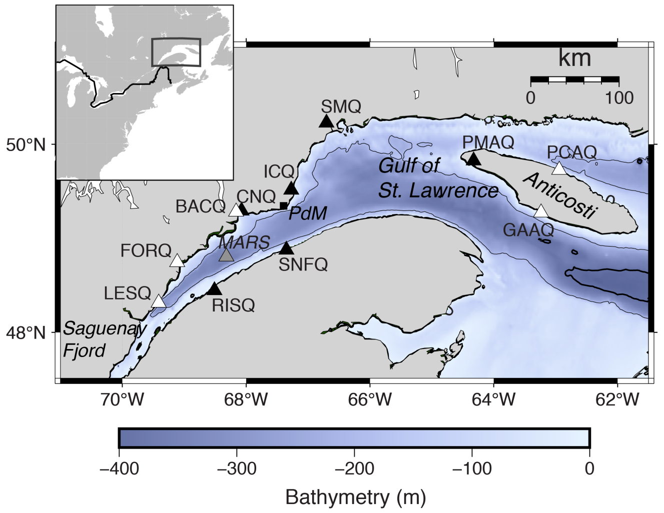

Figure 1 Geographic area, seismic stations and hydrophone distribution. Black triangles: seismometers used in this study. White triangles: additional seismometers used in Plourde and Nedimović (2022) but discontinued in 2019. Grey triangle: MARS hydrophone. Black square: Pointe-des-Monts.

RISQ (Rimouski), CNQ (Côte-Nord), SNFQ (Sainte-Félicité), ICQ (Islets-Carribou), SMQ (St-Marguerite) and PMAQ (Port Menier Anticosti). RISQ, CNQ and SNFQ are located in the Estuary, while ICQ, SMQ and PMAQ are in the Gulf (Fig. 1). Stations ICQ, PMAQ, RISQ, SNFQ use a Nanometrics Trillium 120 s PH Posthole sensor that measured the three-component velocities. The other two instruments, at CNQ and SMQ, use a Geotech S-13 short-period sensor that only measured the vertical component. We used all three data components at stations ICQ, PMAQ, RISQ, SNFQ. Whale calls usually have very similar vertical and horizontal amplitudes at onshore seismometers, so we expect that summing all three-components, to slightly improve SNR. At stations CNQ and SMQ, we only used the vertical component. All instruments have frequency responses that are flat within the 10–32 Hz bands of data processing. All data were recorded at 100 samples per second (100 Hz), and instrument response was not removed. Additionally, acoustic recordings from the University of Québec at Rimouski marine acoustic research station (MARS) were analyzed for fin and blue whale calls. The MARS hydrophone was moored at a water depth of 300 m in the middle of the Laurentian channel and recorded continuously from August to October 2021.

2.2 Detection Method

We follow the whale call detection method developed in the previous work using LSLS land seismometer data from October 2015 to February 2020 (Plourde and Nedimović, 2022). This method relies on the characteristic recurrence intervals of the regularly repeating low-frequency calls, 10–15 s for fin whale 20 Hz calls and 68–78 s for blue whale 16–18 Hz type A-calls (Fig. 2). Northwest Atlantic fin whale 20 Hz calls and blue whale A-calls are known to have relatively consistent intervals (INIs) between individual call units, with songs lasting up to hours (Roy et al., 2018; Simard et al., 2016). Waveforms at land seismometers can pick up on a lot of external noise, and whale calls received at these stations often have a relatively low amplitude. Due to this, if we were to evaluate detections on the temporal scale of an individual call, especially in the case of fin whale calls which last only ~1 s, we think that surrounding noise would trigger detections and increase the likelihood of false positives. As such, we choose to rely on the recurrence intervals of whale calls, rather than individual call detections.

The detection procedure can be divided into 6 steps, as demonstrated by the example with a fin whale detection at PMAQ below (Fig. 3). The seismogram is separated into non-overlapping windows of 120 s and bandpassed between 12–32 Hz (Fig. 3a). Within 120 s and 720 s time windows multiple individual whale calls (usually 7–10) are present if a fin or blue whale is vocalizing, respectively. This provides sufficient seismic data for the detection method to recognize the energy peaks within the frequencies of interest over the recurrence intervals. For each 120 s-window, we compute the power spectrogram $A(t, f)$ from each waveform (Fig. 3b), and then the whale call index $R(t)$ (Fig. 3c), by taking the ratio of the sum of energy in the frequency range of interest (18–21 Hz for fin whales) over the sum of energy outside this frequency band in the spectrogram range, as shown in Equation 1:

$$R(t) = \frac{\int_{f_1}^{f_2} A(t,f)\,df}{\int_{f_3}^{f_4} A(t,f)\,df + \int_{f_5}^{f_6} A(t,f)\,df}, \quad (1)$$

where the frequency limits f_1 to f_6 can be found in Table S1 of the supplementary material. The whale call index is an energy detector similar to those described by Širović et al. (2015) in offshore Southern California and Pilkington et al. (2018) in the Canadian Pacific waters. Next, $P(t, T)$, the secondary power spectrogram is computed from $R(t)$. $W(t)$ is the periodogram of $R(t)$ and is computed by taking the ratio of the sum of power for a period of typical range of whale call internote interval (INI) of 10–13.75 s for fin whales over the sum of power outside the period range (Fig. 3d). If $W(t) > 3.0$, a fin whale detection (FWD) is declared and if there are at least 5 FWDs in a day, it is classified as "active" or else "quiet" day. The threshold $W(t)$ value was chosen to maximize the ratio between the standard deviation and mean detections per day following Plourde and Nedimović (2022), hence to retain the maximum number of detections while minimizing the noise contamination (false positives).

$$W(t) = \frac{\int_{t_1}^{t_2} P(t,T)\,dT}{\int_{t_3}^{t_4} P(t,T)\,dT + \int_{t_5}^{t_6} P(t,T)\,dT}, \quad (2)$$

where period intervals t_1 to t_6 can be found in Table S1. The signal to noise ratio (SNR) is estimated for each fin whale call from the 18–21 Hz seismogram. P_1 (signal) is the mean-square value of a one-second window centered on the peak $R(t)$ value and P_0 (noise) is the mean-square value of the three-second window ending at 0.8 s before that center time.

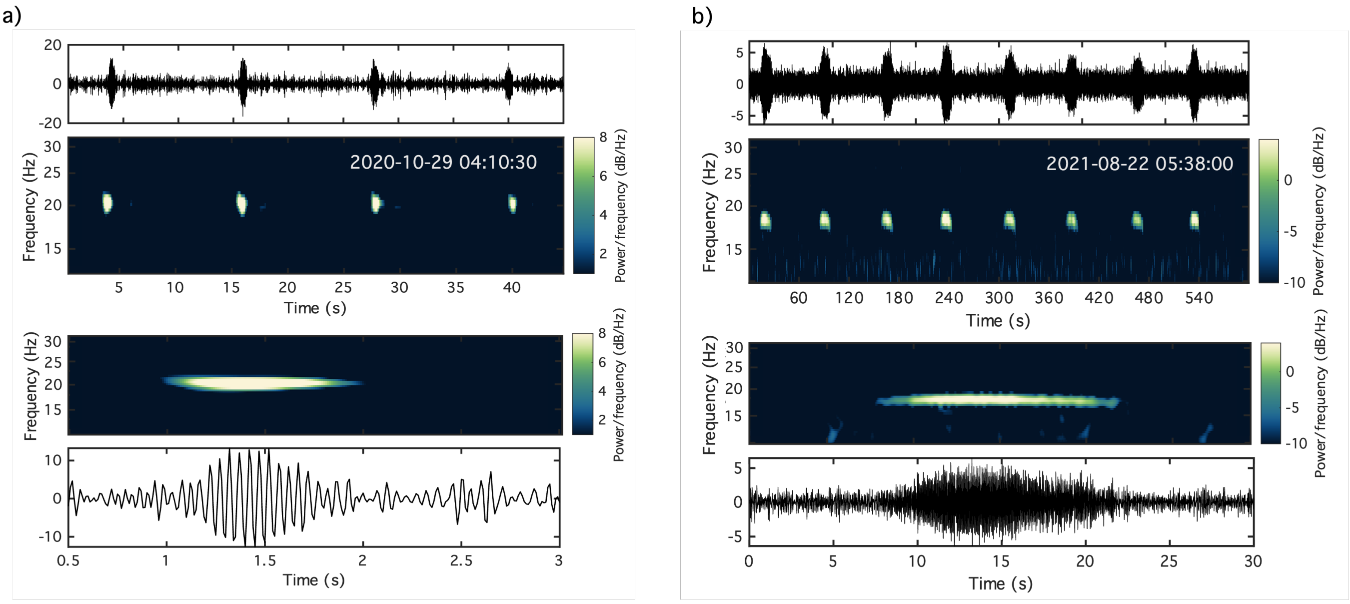

Figure 2 Characteristic waveform and spectrogram of a) fin whale calls at station ICQ (spectrogram parameters: STFT at 48 points with 85% overlap, 12–32 Hz filtered) and b) blue whale type A-calls recorded at station SNFQ (spectrogram parameters: STFT at 48 points with 70% overlap, 10–32 Hz filtered). Bottom panels show the zoom-in of the first call within each series (spectrogram parameters: STFT at 48 points with 95% overlap). Note the y-axis unit for the waveforms is in count. Instrument response was not removed.

$$\mathrm{SNR} = 10 \times \log_{10}\left(\frac{P_1}{P_0}\right) \quad (3)$$

The procedure for blue whale call detection is nearly identical. Since the intervals between blue whale calls are much longer (66–76 s) and the frequency range is slightly lower (16–18.25 Hz), we compute 12 min spectrograms between 10–32 Hz. This longer spectrogram window will have multiple blue whale calls present if it is vocalizing. Equations 1 and 2 for $R(t)$ and $W(t)$ are adjusted respectively, to account for the larger INI (Table S1). If $W(t) > 1.5$ a blue whale detection (BWD) is made, and if there are at least 3 BWDs in a day, it is classified as an "active" day. The SNR is estimated for each individual blue whale call from the 16–18.5 Hz seismogram. P_1 is the mean-square value of a 4 s window centered on the peak $R(t)$ value and P_0 is the mean-square value of the window 20 to 5 s before that center time. A summary of the relevant detection parameters and criteria is listed in Table S1. These user-defined values are not necessarily optimal and need to be fine tuned for applications in the detection of other types of whale calls and/or in other regions. We retain the values chosen by Plourde and Nedimović (2022) as they have been demonstrated to work optimally for the fin and blue whale call detections in the Lower St. Lawrence Seaway. Plourde and Nedimović (2022) created an additional detection algorithm, using a 20 s recurrence interval, targeting the 18–21 Hz band and a $W(t) = 3$ threshold. The primary spectrograms are computed for 1.5 s windows and the secondary spectrogram for 180 s windows. To be considered active, they require four detections (between the fin/blue whale thresholds used in the main algorithms) on a given day. The purpose of this "20 s period test" is to estimate the number of false fin whale and blue whale detections in the catalogue. They estimated a false positive rate of approximately 8.5% for fin whales and 4.8% for blue whales, by comparing the proportion of incorrectly designated active day detections from the 20 s period test and the total amount of active day detections. Since we follow the same parameter choices, we expect the method performance to be highly similar, if not identical.

We compare annual spatiotemporal trends in fin whale and blue whale detections from our catalogue (February 2020 to January 2022) with that of previous years (October 2015 to February 2020) reported by Plourde and Nedimović (2022).

Finally, the MARS hydrophone recording was analyzed by first computing a spectrogram (1 s Hamming window with 50% overlap) for each 5 min sound file (Fig. S1). The series of spectrogram images, representing the dataset, was visually inspected for fin whale and blue whale calls. The presence or absence of each species, per 5 min file, was then reported as a time series.

3 Results

In total, we found 14 076 fin whale detections (28 152 minutes) and 3739 blue whale detections (44 868 minutes) between February 2020 and January 2022 at the six seismometers used in this study (Fig. 4). Typically, there are about 7–10 whale calls within each detection (FWD or BWD). Quiet day detections form 15.9% of the fin whale catalogue and 13.6% of the blue whale catalogue. It is important to note that these results are the sum of all detections across the six seismometers used in the study, therefore it is possible that the same whale call is recorded at more than one station. However, such overlapping detections are likely only a small fraction of the total

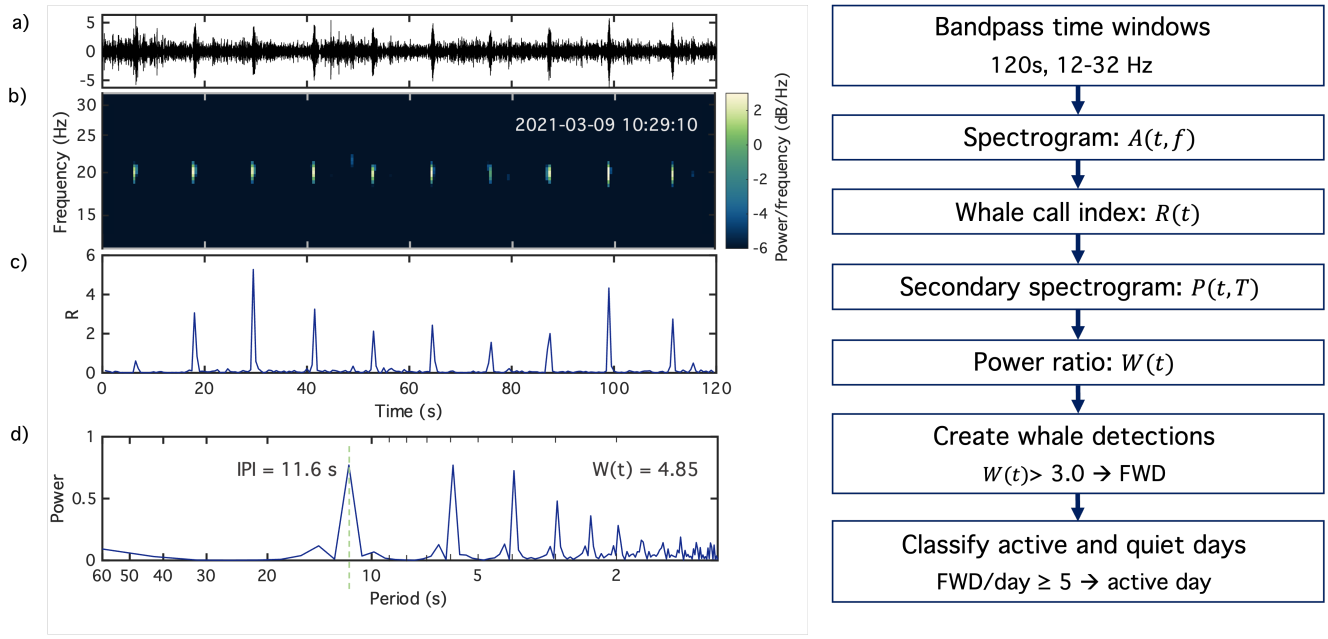

Figure 3 Example of a fin whale call detection procedure, as developed by Plourde and Nedimović (2022), using station PMAQ. a) bandpassed waveform segment, b) associated spectrogram (parameters: STFT at 48 points with a 50% window overlap, 12–32 Hz filtered), c) whale call index (Equation 1), d) periodogram of c) and power ratio (Equation 2).

detections, since the closest inter-station distance is approximately 50 km, which is much greater than the whale-call detection radius of a few kilometers estimated by Plourde and Nedimović (2022) through shared detection times at neighbouring seismometers. In the following sections, we describe the clear spatial and temporal variations revealed by the reception of calls from each species.

3.1 Spatial Variation

Across the LSLS, we find that 82% of fin whale active minutes and 95% of blue whale active minutes were detected by land seismometers located in the Northwest Gulf (SMQ, ICQ, PMAQ). For both species, nearly half of the total detections are at station ICQ, the region where the St. Lawrence Estuary opens into the Gulf. On the other hand, the proportion of detections at station PMAQ, on the west end of Anticosti Island, is quite different between species. PMAQ appears more favoured by blue whales, while fin whale detections are slightly more evenly distributed across stations.

In earlier years, between October 2015 to January 2020, it was also observed that relative to fin whales, blue whale detections are skewed downstream towards the Gulf (Plourde and Nedimović, 2022). We find relatively consistent detection patterns across stations SNFQ, CNQ and SMQ used in this study and the 2015–2020 study, for both whale species (Plourde and Nedimović, 2022). Over the 3.5 years of data at ICQ, fin whale detections remain elevated, with over 3600 detections per year (Table S1a). Blue whale detections at ICQ were less consistent, demonstrated by a 54% decrease in detections over the year 2021 compared to the average number of annual detections in 2019 and 2020 (Table S1b). Meanwhile, we find a significant increase in detections for both species over the past 7 years at station PMAQ, around the Anticosti Island. Fin whale and blue whale detections at PMAQ increased on average by 374 detections (748-minutes) per year and by 163 detections (1950 minutes) per year, respectively, with the highest number of detections in 2021 for both species in this region (Table S1a, b).

3.2 Temporal Variation

In terms of temporal variation, both whale species were mainly detected during the second half of the year. On average, 87% of fin whale detections and 71% of blue whale detections (active days) were from September to January. Although there is some variation in the monthly range of detections, fin whale detections were mostly concentrated in the fall and early winter (September to February), whereas blue whale detections were found throughout the winter season (September to April). For instance, multiple blue whales were detected throughout April in 2020 (only at station PMAQ) and March in 2021 (at both stations ICQ and PMAQ). From May to August, there were negligible fin whale detections and blue whale detections at land seismometers throughout the LSLS (Fig. 4).

These temporal trends agree with previous studies detecting fin whale 20 Hz calls and blue whale type A-calls in the LSLS (Simard et al., 2016; Roy et al., 2018; Plourde and Nedimović, 2022). However, the October 2015 to January 2020 average fraction of September–January detections from the Plourde and Nedimović (2022) study are 10% and 20% higher for fin whales and blue whales, respectively, than our 2020–2021 results. When summarizing the past 7 years of land seismometer data into a winter group (September to April) and a summer group (May to August), we observe a relatively longer cumulative duration of active calls in the winter for both fin whales and blue whales over the recent

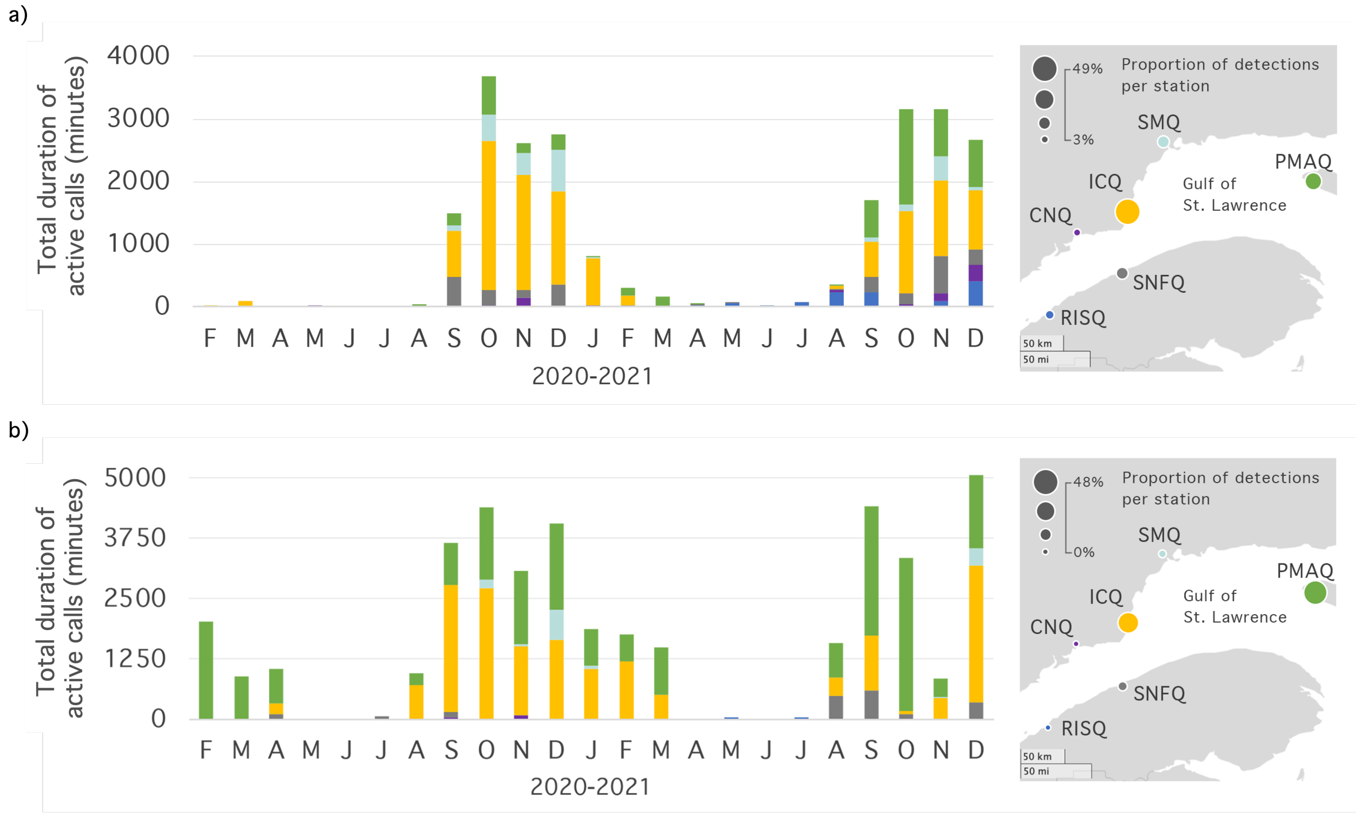

Figure 4 (Left) Monthly distribution of active minutes of whale calls, and (right) proportions of detections per station represented spatially, for a) fin whales and b) blue whales between February 2020 and January 2022.

years (2019–2021) (Fig. 5).

3.3 Comparison to Hydrophone Catalogue and Detection Range

We compare both fin whale and blue whale detections from the MARS hydrophone to those at the closest (∼25 km) land seismometer in Rimouski (RISQ) during August and September 2021. As shown in Fig. 6, the land seismometer detections on average constituted only 1% of the total hydrophone detections (note the logarithm scale in detection minutes). Fin whale and blue whale songs can persist up to many hours, therefore we do not think the spectrogram windows of slightly different length analyzed by each study used to declare a detection impacts our comparison results significantly. The hydrophone dataset contains higher frequency whale vocalizations that were not recorded by the seismometer due to its lower sampling rate. Over the two month recording period, there were no instances of blue whale D-calls vocalized without A-calls. D-calls were identified in only 25% of 5 min time windows with the stereotyped songs. Therefore, during this time period, the nearby land seismometer would not have missed any whale activities due to its bandwidth limit.

4 Discussion

4.1 Performance of Detection Method

The characteristic recurrence power ratio methodology used in this study appears to produce robust results, following similar spatiotemporal whale detection patterns noted by previous studies in the LSLS (Roy et al., 2018; Simard et al., 2016). The minimum number of detections within a day to be considered "active" serves as a first way to eliminate likely false detections. Out of the total number of detections labelled using this method, 86.4% and 84.1% of blue whale and fin whale detections respectively were classified as "active". Plourde and Nedimović (2022) estimated a false positive rate of 8.5% for fin whales and 4.8% for blue whales, respectively for active day detections. Since we do not change any of the detection parameters, we assume this estimate is likely very similar for this 2020–2021 catalogue.

4.2 Variation between the St. Lawrence Estuary and Gulf

Most whale detections were found by stations located in the Northwest Gulf. This is inevitably partially biased towards the locations of the seismometers used in this study. For instance, this study does not consider the mouth of the Saguenay Fjord, one of Canada's marine protected areas, which has been shown by previous studies to be an important foraging ground for whales (Simard and Roy, 2018), and where a land seismometer (LESQ) near this location demonstrated very high fin whale detection rates and relatively low blue whale detections between 2015–2019 (Plourde and Nedimović, 2022). However, LESQ was decommissioned in 2019, thus not used in the current study. This suggests that the proportion of fin whale detections would likely be more evenly distributed within the Estuary and Gulf if

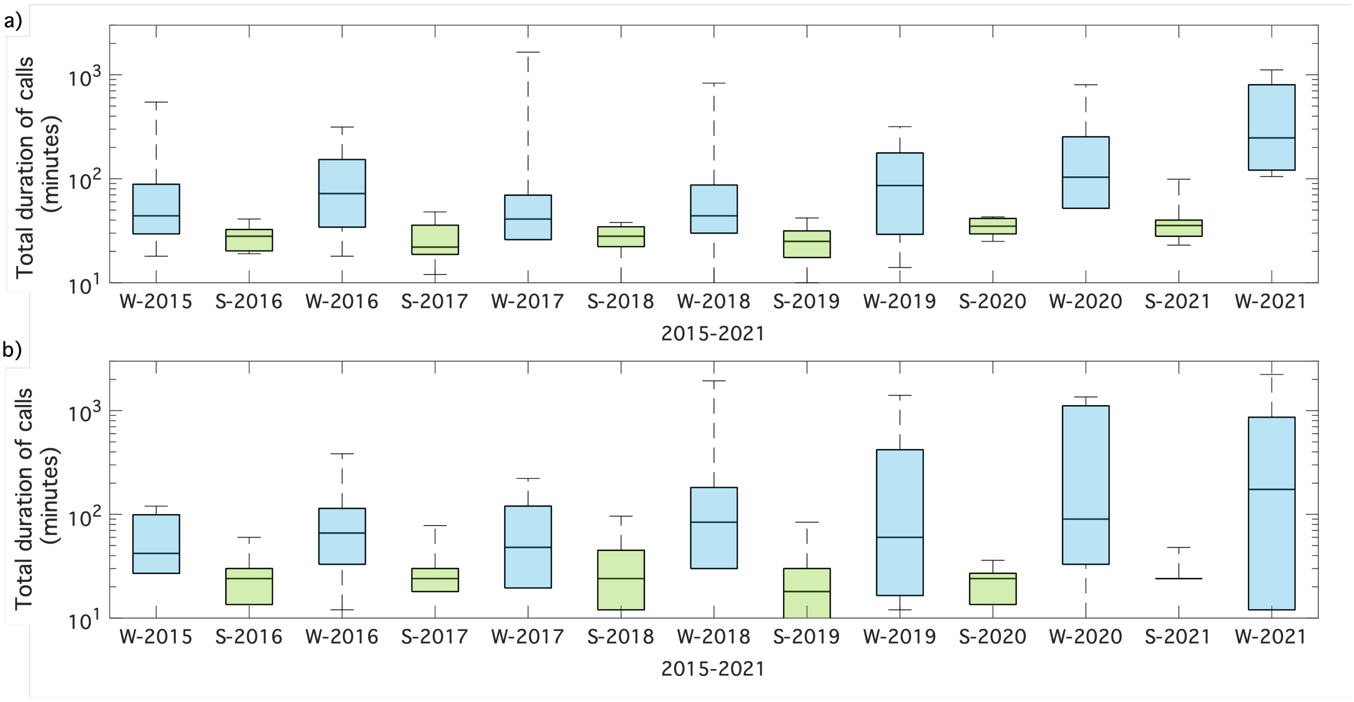

Figure 5 Summary of winter (September–April) and summer (May–August) median detections across all available stations between October 2015 and January 2022 (from Plourde and Nedimović (2022) and this study) for a) fin whales and b) blue whales. The central line on each box refers to the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the maximum and minimum data points.

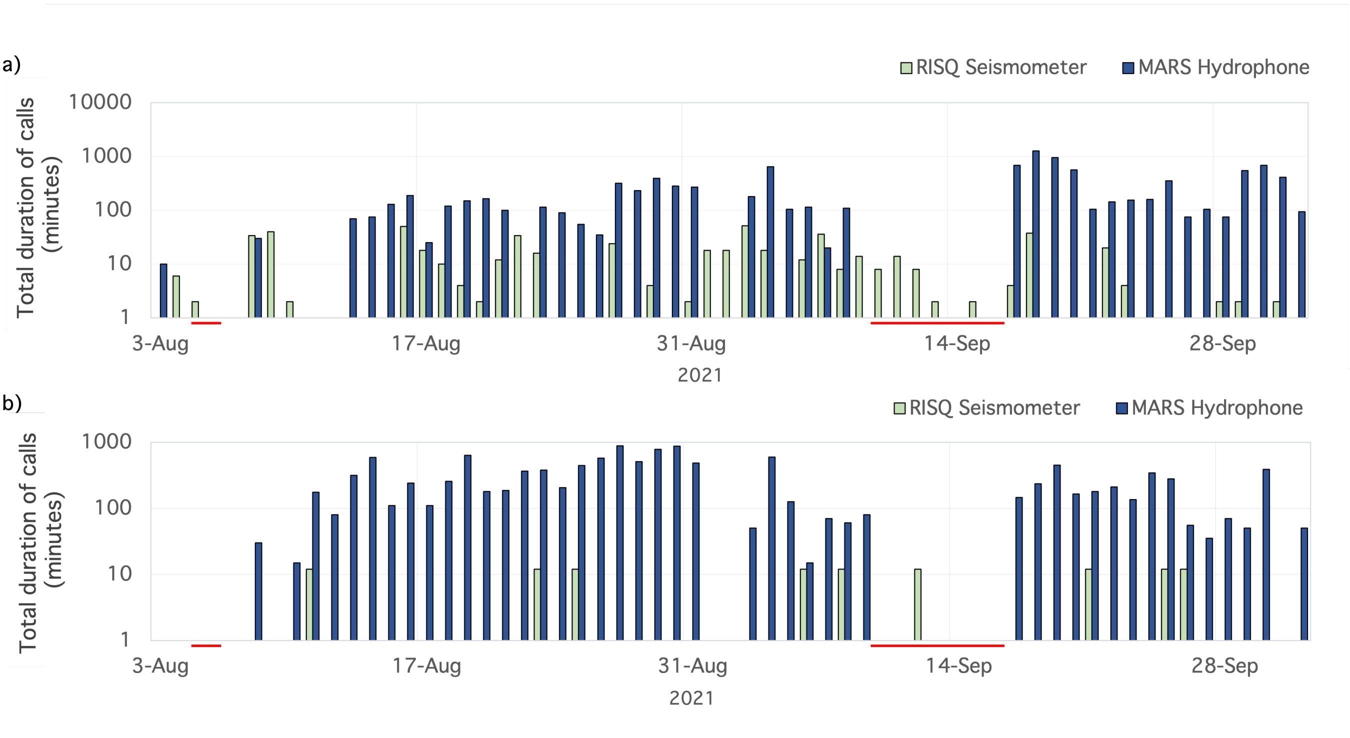

Figure 6 Distribution of minutes recorded at RISQ seismometer and MARS hydrophone during August and September 2021, for a) fin whales and b) blue whales. Red lines indicate inactive periods of the hydrophone.

detections were possible and included from the Saguenay region (Fig. 4).

Spatial differences in call detection between species may be due to factors such as preferential diet and water depth. Fin whales are considered generalist feeders, eating a large variety of zooplankton, whereas blue whales are specialists, feeding almost exclusively on krill (Lesage et al., 2017). The more flexible niche of fin whales may explain the slightly more evenness in distribution of detections across stations. On the other hand, the Gaspé Current brings large volumes of freshwater from the Estuary moving along the south shore towards the Southern Gulf, including small organisms which often get trapped by the cyclonic Anticosti Gyre, where they can remain in this circulation for periods of up to six months (Sourisseau et al., 2006). Wind driven upwelling events further accumulate krill along the north shore (Sourisseau et al., 2006). This could be a viable mechanism for the concentration of blue whale call detections in the Northwest Gulf (a combined 92% at stations ICQ and PMAQ). Other than prey distinctions, preferential water depth is another niche characteristic that differs between species and may further explain spatial patterns. Previous studies found that fin whale 20 Hz calls are typically produced in shallow water environments (30–100 m), whereas blue whale A-calls are often produced in deeper waters (340–450 m) (Davis et al., 2020; Stafford et al., 2007). The stations in the Estuary RISQ and CNQ have very shallow bathymetry near the shores, therefore it is not surprising that negligible blue whale calls were detected at these stations. If blue whales were present and vocalizing at their preferential water depths, they would have likely been too far offshore to be detected by stations RISQ and CNQ.

4.3 Seasonal Variation, Relation to Marine Environmental Factors and Biological Productivity

The St. Lawrence is commonly referred to as a summer feeding ground for marine mammals, due to oceanic processes such as tidal interactions with bathymetry, wind driven upwelling and mean circulation that easily aggregate prey (Sourisseau et al., 2006). However, our results (Fig. 4) as well as other seismic and acoustic studies detecting fin whale 20 Hz and blue whale A-calls in this region find a sudden drop in call detections from May to August (Simard et al., 2016; Roy et al., 2018; Plourde and Nedimović, 2022). When considering prey availability, visual sightings, and the acoustic presence of other call types during the summer months, we find it is likely that fin whales and blue whales are present in the LSLS though not vocalizing the calls the seismometers are able to track (Ramp and Sears, 2012; Ramp et al., 2015). For instance, blue whale D-calls, intermittent 40 Hz (close to the Nyquist frequency of 50 Hz at all the land seismometers) vocalizations associated with foraging behaviour, have been found to persist throughout the summer months from a 2010–2015 hydrophone study in the LSLS (Simard et al., 2016). Acoustic studies showed similar findings, that is, fin whale 20 Hz and blue whale A-calls are not produced often during the summer months, or the foraging season, near the Azores, mid Atlantic (Romagosa et al., 2021), in Northern Icelandic waters (Akamatsu et al., 2014), and in the Gulf of Alaska (Stafford et al., 2007). In fact, these calls are only produced by males and thus are believed to be a reproductive display (Croll et al., 2002). The detection results in this paper and others relying uniquely on fin whale 20 Hz and blue whale A-calls should be treated as a minimum presence of whale activity, since these whales produce a variety of calls associated with different functions (Romagosa et al., 2021; Simard et al., 2016).

Fin whale 20 Hz calls and blue whale A-calls are typically detected in the Estuary starting in August. The higher frequency vocalizations produced by fin whales and blue whales are dominant on feeding grounds during the summer, with low vocalization rates outside these months (Romagosa et al., 2021; Širović and Oleson, 2022). From the two-month (August–September 2021) hydrophone catalogue presented in this study, we observe that blue whale D-calls are still present, although they are rare and of short duration compared to stereotyped songs (Fig. S6). The whales are forced out of the Lower Estuary by December/January when ice cover begins to accumulate and move downstream towards the Gulf. It is commonly assumed that these baleen whales are also forced to exit the Gulf due to thick sea ice obstructions (Delarue et al., 2008). However, we find whale detections during the winter season from land seismometers and hydrophones throughout the Gulf region (Simard et al., 2016; Roy et al., 2018; Plourde and Nedimović, 2022). Similarly, a satellite tagging study found that some blue whales remain in the Gulf over the winter, while others depart the feeding ground in late fall to move towards the New England Seamounts, suggesting that a portion of the population are remaining in the productive waters of the St. Lawrence during the winter breeding season (Lesage et al., 2017). Recently, warmer intermediate and deep waters have been observed in parts of the channels and around the Anticosti Island (Galbraith et al., 2021). The sea ice cover in the Gulf hit a record low during the 2020–2021 winter for the first time since 1968, according to the Canadian Ice Service. Meanwhile we observe a high amount of winter whale detections in the same year (Fig. 5). Warmer intermediate and deep waters reducing sea ice cover in LSLS could be opening corridors in the Northwest Gulf, allowing some whales to remain in this sub-arctic region during winter months. Species distribution models have found that fin whale habitat suitability is high at locations with relatively low (<20%) sea ice concentration, potentially making the LSLS a favourable winter ground in the future (Duengen et al., 2022). The changing winter sea ice dynamics in a warming LSLS will have implications for the marine ecosystem, due to its influence on water mass characteristics and nutrient availability (Urrego-Blanco and Sheng, 2014).

4.4 Comparison to Hydrophone and Detection Range

For a given recorder setup and type of whale call, the detection area of a hydrophone is mainly dependent on the local bathymetry, water mass characteristics and ship traffic in the location of the station (Simard et al., 2016). It has been estimated that the detection area of hydrophones in the Estuary and the widest region of the Gulf can reach approximately 80 km and 250 km, respectively, assuming that any call with an SNR > 0 dB can be detected (Simard et al., 2016; Roy et al., 2018). However, detection range modelling studies in other regions have found much smaller ranges of about 30–40 km, with decreasing probability of detecting distinct baleen whale calls beyond this distance (Stafford et al., 2007; Cholewiak et al., 2018). When a whale produces a call, the first acoustic wave that reaches the receiver is usually a direct wave, travelling in the water column from the whale to the hydrophone. Meanwhile, whale calls received at the land seismometers travel through multiple interfaces including water, sediment, and bedrock, and hence experience a larger amount of energy loss due to impedance contrast (Plourde and Nedimović, 2022). As such the detection radius of a land seismometer is likely on the order of a few kilometers, as estimated by Plourde and Nedimović (2022) through shared detection times at neighbouring seismometers in the LSLS, substantially smaller than that of a hydrophone. This large difference in their detection ranges may explain the orders of magnitude contrast in the detection minutes at RISQ and MARS hydrophone, in addition to the hydrophone being moored in the deepest part of the Laurentian Channel, close to the steep bathymetric features at its north. The MARS hydrophone is located closer to the Saguenay Marine Park, where there is a strong density front and steep bathymetry, creating more favourable conditions for whales (Fig. 6). However it is also important to note that the vast majority of whale calls received at RISQ are of low quality. Only 0.3% of calls have an R value greater than 3 and SNR greater than 1. RISQ is located in a relatively urban zone compared to the other land seismometers which may result in other noises conflicting with the target frequency of whales. Another direct comparison between a hydrophone and a land seismometer with high detections of both species and a larger proportion of higher quality calls, such as stations ICQ or PMAQ, would be beneficial to directly compare waveforms of the same calls. However, hydrophone deployment in the LSLS has been largely focused near the Escoumins/Saguenay region and Southern Gulf of the St. Lawrence.

The seismogram for whale call detections is presented in the raw format (unit in count) for direct comparisons to the previous study (Plourde and Nedimović, 2022). In another seismic ground motion study, we removed the instrument responses and compared the true ground velocities of several fin whale calls recorded at station LESQ (Les Escoumins) to different types of cultural noises. The peak ground velocity (PGV) of a fin whale call, likely within a few kilometers from LESQ, is on the order of 10^{-6} to 10^{-7} $\mathrm{m/s}$, which is about two orders of magnitude lower than the PGVs of a passenger train recorded at 10–20 m away from the railway track or snow plows driving in front of residential buildings in Montréal (Liu and Chien, 2023).

4.5 Limitations and Application of Deep Learning to Detecting Whale Calls

Automated detectors have greatly increased the efficiency of searching for stereotyped signals of interest in passive acoustic monitoring (PAM) datasets, by relying on pre-defined detection parameters (e.g., energy threshold in frequency band, internote intervals) characteristic of a whale population in a specific region. Recently, there have been several successful applications of convolutional neural networks (CNN), a class of deep learning (DL) networks originally proposed for image classification tasks, to detect various vocalizations produced by killer whales (Bergler et al., 2019), sperm whales (Bermant et al., 2019), beluga whales (Zhong et al., 2020), North Atlantic right whales (Kirsebom et al., 2020; Shiu et al., 2020), humpback whales (Allen et al., 2021), fin whales (Madhusudhana et al., 2021) and blue whales (Rasmussen and Širović, 2021). The clear advantage of DL is its capacity to adapt with training data distribution, rather than be constrained by parameters crafted from domain-knowledge exemplified by the Plourde and Nedimović (2022) algorithm. The flexibility and capacity associated with the DL-based method would be beneficial in future studies for a few reasons. First, it could be used to detect non-stereotyped vocalizations such as the fin whale 40 Hz and blue whale D-calls (Rasmussen and Širović, 2021). These are traditionally identified manually in spectrograms, which is not ideal for large datasets. Including both foraging vocalizations and songs in the entire analysis would result in a more accurate estimation of spatial and temporal patterns of fin whales and blue whales. Second, DL can also be used to improve detection of songs by training the algorithm with scenarios of variable acoustic conditions (e.g., temporal and spatial characteristics), as well as exposure to different types of environmental noise (Allen et al., 2021).

To develop a DL model, a large number of annotated examples are required to train and evaluate a classifier. We suggest that the whale detection catalogue created in this study can provide a basis for the development of such a model, with fine-tuning to address some of the limitations of the Plourde and Nedimović (2022) detection algorithm used in the current study. First, this algorithm cannot be evaluated properly due to the lack of ground-truth labels. For instance, it is impossible to know its accuracy and whether the algorithm predicts a true positive or false positive and hence its recall and precision. These metrics, as well as their derivatives (e.g., F1-score, which assesses the predictive skill of a model), are fundamental to our understanding of its performance and its application to real-world scenarios. To address this limitation, we propose constructing a whale call dataset annotated by human experts, which can serve as a benchmark to evaluate the Plourde and Nedimović (2022) algorithm as well as potential detection algorithms developed in the future. One possible way for dataset construction is to filter the data catalogue from this study and Plourde and Nedimović (2022) manually to remove false positives. Second, the detection by Plourde and Nedimović (2022) is made based on a group of individual whale calls with each call group defined as a detection. This prohibits the model from being applied to scenarios where only individual whale calls are available (e.g., other calls are lost due to data transmission issues). A deep learning-based model trained on call-level (in contrast to detection-level) data can mitigate this problem. Third, many automatic detection algorithms, including the one used in this study, for monitoring whale calls do not consider variable acoustic conditions (Madhusudhana et al., 2021). The LSLS land seismometer whale detection catalogue, combining the results from this study and Plourde and Nedimović (2022), consists of nearly 7 years of labelled stereotyped fin whale and blue whale calls. These whale call signals were detected over a wide spatial extent from the Estuary to the Gulf of St. Lawrence, throughout all seasons and over multiple years. The use of a DL-based model trained on this dataset (with annotations) could be particularly useful to detect and classify whale calls exposed to different environmental conditions, or signal context.

Within a single population, INIs and frequency limits of calls can change over time (Rice et al., 2022; Romagosa et al., 2021). Previous PAM datasets from 1998–2001 have shown that fin whale INIs used to be about 7 s longer than the current 12 s, in the central and eastern North Atlantic Ocean (Romagosa et al., 2021). This INI shift occurred over four years, a relatively short amount of time, with the 12 s INI becoming dominant as of 2004 (Romagosa et al., 2021). Additionally, the peak frequency of both fin whale and blue whale stereotyped songs have been decreasing in nearly all ocean basins, since first recorded in the 1960s (Rice et al., 2022; Weirathmueller et al., 2017). The potential variability of INI and peak frequency of whale songs is important to note when using the characteristic recurrence method since it relies on these features for detection. However, there is typically a transitional period associated with these changes and the parameters of our detection algorithm can be adjusted as needed. A future DL-based algorithm can test the performance of such algorithms over long timescales to observe the impacts of these variations in whale song structures.

5 Conclusion

Following a detection method that relies on the characteristic recurrence intervals of the regularly repeating low-frequency whale calls developed by Plourde and Nedimović (2022), we find that land seismometer detections follow the overall pattern of hydrophones, with most detections from fall to early winter in the Estuary and until mid-winter/spring in the Gulf. As such, we consider land seismometers to be an effective tool to detect whales and indicate regional aggregation areas due to the narrow detection range. For instance, high detection rates at stations ICQ and PMAQ suggests that the Northwest Gulf is an important region for both species, especially blue whales. This productive region previously known to be important for whales during the summer foraging season has been shown by land seismometers to be a region of interest also during the winter months, notably over recent years where we observe a relatively longer winter residence time in the LSLS. These results support the emerging idea that the migratory behaviour of baleen whales is more complex than the traditional assumption that whales travel strictly between low latitude breeding grounds and high latitude feeding grounds (Simon et al., 2010).

These results have implications for the relative timing and regions of focus for marine mammal protection policies. The labelled whale detection catalogue developed in this study may be suitable for training a deep learning method for classifying and predicting fin whale and blue whale calls in the LSLS region. A better understanding of the biological and physical mechanisms driving whale habitat usage and how these are expected to change over time in a warming climate is essential for making informed decisions on shipping and fishing, reducing whale collision risks and mitigating noise pollution.

Acknowledgements

Support for this work was provided by the Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant RGPIN-2018-05389 and by the Fonds de recherche du Québec - Nature et technologies. The underwater acoustic dataset was collected and processed within the MARS project (www.projet-mars.ca/en) co-led by ISMER and Innovation maritime, and funded by Transport Canada, the Ministère de l'Économie, de l'Innovation et de l'Énergie and the St. Lawrence Economic Development Council (SODES). The Editor thanks Alex Saoulis and an anonymous reviewer for the time taken to review this paper.

Data and Code Availability

All seismic data were downloaded through the EarthScope Consortium Web Services (https://service.iris.edu/), including the following seismic network: (1) CN (Natural Resources Canada, 1975). The supplementary information for this article includes Table S1, Figure S1–S6, along with Table S2–S3 (whale call detection catalogue), Movie S1 and the MATLAB whale detection code available on Zenodo (Goblot et al., 2024).

Competing interests

The authors have no competing interests.

References

Akamatsu, T., Rasmussen, M., and Iversen, M. Acoustically invisible feeding blue whales in Northern Icelandic waters. *The Journal of the Acoustical Society of America*, 136(2):939–944, Aug. 2014. doi: 10.1121/1.4887439.

Allen, A. N., Harvey, M., Harrell, L., Jansen, A., Merkens, K. P., Wall, C. C., Cattiau, J., and Oleson, E. M. A Convolutional Neural Network for Automated Detection of Humpback Whale Song in a Diverse, Long-Term Passive Acoustic Dataset. *Frontiers in Marine Science*, 8, 03 2021. doi: 10.3389/fmars.2021.607321.

Bergler, C., Schröter, H., Cheng, R. X., Barth, V., Weber, M., Nöth, E., Hofer, H., and Maier, A. ORCA-SPOT: An Automatic Killer Whale Sound Detection Toolkit Using Deep Learning. *Scientific Reports*, 9(1), 07 2019. doi: 10.1038/s41598-019-47335-w.

Bermant, P. C., Bronstein, M. M., Wood, R. J., Gero, S., and Gruber, D. F. Deep Machine Learning Techniques for the Detection and Classification of Sperm Whale Bioacoustics. *Scientific Reports*, 9(1), 08 2019. doi: 10.1038/s41598-019-48909-4.

Bouffaut, L., Madhusudhana, S., Labat, V., Boudraa, A.-O., and Klinck, H. A performance comparison of tonal detectors for low-frequency vocalizations of Antarctic blue whales. *The Journal of the Acoustical Society of America*, 147(1):260–266, 01 2020. doi: 10.1121/10.0000609.

Bouffaut, L., Taweesintananon, K., Kriesell, H. J., Rørstadbotnen, R. A., Potter, J. R., Landrø, M., Johansen, S. E., Brenne, J. K., Haukanes, A., Schjelderup, O., and Storvik, F. Eavesdropping at the Speed of Light: Distributed Acoustic Sensing of Baleen Whales in the Arctic. *Frontiers in Marine Science*, 9(4), July 2022. doi: 10.3389/fmars.2022.901348.

Brodie, D. C. and Dunn, R. A. Low frequency baleen whale calls detected on ocean-bottom seismometers in the Lau basin, southwest Pacific Ocean. *The Journal of the Acoustical Society of America*, 137(1):53–62, 2015. doi: 10.7567/JJAP.54.07HG03.

Cholewiak, D., Clark, C., Ponirakis, D., Frankel, A., Hatch, L., Risch, D., Stanistreet, J., Thompson, M., Vu, E., and Van Parijs, S. Communicating amidst the noise: modeling the aggregate influence of ambient and vessel noise on baleen whale communication space in a national marine sanctuary. *Endangered Species Research*, 36:59–75, May 2018. doi: 10.3354/esr00875.

Croll, D., Clark, C., Acevedo, A., Tershie, B., Flores, S., Gedamke, J., and Urban, J. Only male fin whales sing loud songs. *Nature*, 417 (6891):809–809, June 2002. doi: 10.1038/417809a.

Davis, G. E., Baumgartner, M. F., Corkeron, P. J., Bell, J., Berchok, C., Bonnell, J. M., Bort Thornton, J., Brault, S., Buchanan, G. A., Cholewiak, D. M., Clark, C. W., Delarue, J., Hatch, L. T., Klinck, H., Kraus, S. D., Martin, B., Mellinger, D. K., Moors-Murphy, H., Nieukirk, S., Nowacek, D. P., Parks, S. E., Parry, D., Pegg, N., Read, A. J., Rice, A. N., Risch, D., Scott, A., Soldevilla, M. S., Stafford, K. M., Stanistreet, J. E., Summers, E., Todd, S., and Van Parijs, S. M. Exploring movement patterns and changing distributions of baleen whales in the western North Atlantic using a decade of passive acoustic data. *Global Change Biology*, 26(9):4812–4840, May 2020. doi: 10.1111/gcb.15191.

Delarue, J., Todd, S., Van Parijs, S., and Di Iorio, L. Geographic variation in northwest Atlantic fin whale (Balaenoptera physalus) song: Implications for stock structure assessment. *The Journal of the Acoustical Society of America*, 124(4 Supplement): 2507–2507, Oct. 2008. doi: 10.1121/1.4782885.

Dréo, R., Bouffaut, L., Leroy, E. C., Barruol, G., and Samaran, F. Baleen whale distribution and seasonal occurrence revealed by an ocean bottom seismometer network in the Western Indian Ocean. *Deep Sea Research Part II: Topical Studies in Oceanography*, 161:132–144, 2019. doi: 10.1016/J.DSR2.2018.04.005.

Duengen, D., Burkhardt, E., and El-Gabbas, A. Fin whale (Balaenoptera physalus) distribution modeling on their Nordic and Barents Seas feeding grounds. *Marine Mammal Science*, 38(4): 1583–1608, May 2022. doi: 10.1111/mms.12943.

Dunn, R. A. and Hernandez, O. Tracking blue whales in the eastern tropical Pacific with an ocean-bottom seismometer and hydrophone array. *The Journal of the Acoustical Society of America*, 126(3):1084–1094, Sept. 2009. doi: 10.1121/1.3158929.

Franek, P., Plaza-Faverola, A., Mienert, J., Buenz, S., Ferré, B., and Hubbard, A. Microseismicity Linked to Gas Migration and Leakage on the Western Svalbard Shelf. *Geochemistry, Geophysics, Geosystems*, 18(12):4623–4645, 2017. doi: 10.1002/2017GC007107.

Galbraith, P., Chassé, J., Shaw, J.-L., Dumas, J., Caverhill, C., Lefaivre, D., and Lafleur, C. Physical Oceanographic Conditions in the Gulf of St. Lawrence during 2020. *DFO Can. Sci. Advis. Sec. Res. Doc*, (2021/045):iv–81, June 2021. https://www.dfo-mpo.gc.ca/csas-sccs/Publications/ResDocs-DocRech/2021/2021%5F045-eng.html.

Goblot, E., Yajing, L., Plourde, A., Cauchy, P., Mérindol, J., Bernier, C., Li, G., and Roth, B. Data and Code: Spatiotemporal Variability of Fin Whale and Blue Whale Calls Detected by Land Seismometers in the Lower St. Lawrence Seaway (dataset). May 2024. doi: 10.5281/zenodo.10028774.

Hodul, M., Knudby, A., McKenna, B., James, A., Mayo, C., Brown, M., Durette-Morin, D., and Bird, S. Individual North Atlantic right whales identified from space. *Marine Mammal Science*, 39(1), 2023. doi: 10.1111/mms.12971.

Kirsebom, O. S., Frazao, F., Simard, Y., Roy, N., Matwin, S., and Giard, S. Performance of a deep neural network at detecting North Atlantic right whale upcalls. *The Journal of the Acoustical Society of America*, 147(4):2636–2646, 04 2020. doi: 10.1121/10.0001132.

Kuna, V. M. and Nábělek, J. l. Seismic crustal imaging using fin whale songs. *Science*, 371(6530):731–735, Feb. 2021. doi: 10.1126/science.abf3962.

Lesage, V., Gavrilchuk, K., Andrews, R. D., and Sears, R. Foraging areas, migratory movements and winter destinations of blue whales from the western North Atlantic. *Endangered Species Research*, 34:27–43, May 2017. doi: 10.3354/esr00838.

Liu, Y. and Chien, J. Characterizing ground motion from induced seismicity in the context of cultural noises Technical Report II: Cultural noise datasets and comparison to induced earthquakes. Technical report, McGill University, Department of Earth and Planetary Sciences, 04 2023. https://www.bcogris.ca/files/projects/operations-local-issues/QOL-2022-01-Final-Report-Character-Ground-Motion-McGill.pdf.

Madhusudhana, S., Shiu, Y., Klinck, H., Fleishman, E., Liu, X., Nosal, E.-M., Helble, T., Cholewiak, D., Gillespie, D., Širović, A., and Roch, M. A. Improve automatic detection of animal call sequences with temporal context. *Journal of The Royal Society Interface*, 18(180), 2021. doi: 10.1098/rsif.2021.0297.

Matias, L. M. and Harris, D. V. A single-station method for the detection, classification and location of fin whale calls using ocean-bottom seismic stations. *The Journal of the Acoustical Society of America*, 138(1):504–520, 2015. doi: 10.1121/1.4922706.

Mellinger, D. K. and Clark, C. W. Recognizing transient low-frequency whale sounds by spectrogram correlation. *The Journal of the Acoustical Society of America*, 107(6):3518–3529, 06 2000. doi: 10.1121/1.429434.

Mellinger, D. K. and Clark, C. W. Blue whale (Balaenoptera musculus) sounds from the North Atlantic. *The Journal of the Acoustical Society of America*, 114(2):1108–1119, 2003.

Natural Resources Canada. Canadian National Seismograph Network. 1975. doi: 10.7914/SN/CN.

Pilkington, J., Stredulinsky, E., Abernethy, R., and Ford, J. Patterns of Fin whale (Balaenoptera physalus) Seasonality and Relative Distribution in Canadian Pacific Waters Inferred from Passive Acoustic Monitoring. *DFO Can. Sci. Advis. Sec. Res. Doc*, (2018/032):vi–26, sep 2018. https://www.dfo-mpo.gc.ca/csas-sccs/Publications/ResDocs-DocRech/2018/2018%5F032-eng.html.

Plourde, A. P. and Nedimović, M. R. Monitoring fin and blue whales in the lower St. Lawrence Seaway with onshore seismometers. *Remote Sensing in Ecology and Conservation*, 8(4):551–563, Mar. 2022. doi: 10.1002/rse2.261.

Ramp, C. and Sears, R. Distribution, densities, and annual occurrence of individual blue whales (Balaenoptera musculus) in the Gulf of St. Lawrence, Canada from 1980-2008. *DFO Can. Sci. Advis. Sec. Res. Doc*, (2012/157):vii–37, 2012. https://www.dfo-mpo.gc.ca/csas-sccs/Publications/ResDocs-DocRech/2012/2012%5F157-eng.html.

Ramp, C., Delarue, J., Palsbøll, P. J., Sears, R., and Hammond, P. S.

Adapting to a Warmer Ocean–Seasonal Shift of Baleen Whale Movements over Three Decades. *PLOS ONE*, 10(3):1–15, Mar. 2015. doi: 10.1371/journal.pone.0121374.

Ramp, C., Gaspard, D., Gavrilchuk, K., Unger, M., Schleimer, A., Delarue, J., Landry, S., and Sears, R. Up in the air: drone images reveal underestimation of entanglement rates in large rorqual whales. *Endangered Species Research*, 44, Jan. 2021. doi: 10.3354/esr01084.

Rasmussen, J. H. and Širović, A. Automatic detection and classification of baleen whale social calls using convolutional neural networksa. *The Journal of the Acoustical Society of America*, 149 (5):3635–3644, 05 2021. doi: 10.1121/10.0005047.

Rice, A., Širović, A., Hildebrand, J. A., Wood, M., Carbaugh-Rutland, A., and Baumann-Pickering, S. Update on frequency decline of Northeast Pacific blue whale (Balaenoptera musculus) calls. *PLOS ONE*, 17(4):1–14, 04 2022. doi: 10.1371/journal.pone.0266469.

Romagosa, M., Pérez-Jorge, S., Cascão, I., Mouriño, H., Lehodey, P., Pereira, A., Marques, T. A., Matias, L., and Silva, M. A. Food talk: 40-Hz fin whale calls are associated with prey biomass. *Proceedings of the Royal Society B: Biological Sciences*, 288(1954): 20211156, July 2021. doi: 10.1098/rspb.2021.1156.

Romagosa, M., Nieukirk, S., Cascão, I., Marques, T. A., Dziak, R., Royer, J.-Y., O'Brien, J., Mellinger, D. K., Pereira, A., Ugalde, A., Papale, E., Aniceto, S., Buscaino, G., Rasmussen, M., Matias, L., Prieto, R., and Silva, M. A. Fin whale song evolution in the North Atlantic. *eLife*, 13, 01 2024. doi: 10.7554/eLife.83750.

Roy, N., Simard, Y., Aulanier, F., and Giard, S. Fin whale continuous frequentation of St. Lawrence habitats detected from multi-year passive acoustic monitoring (PAM). *DFO Can. Sci. Advis. Sec. Res. Doc*, (2018/059):vi–14, May 2018. https://www.dfo-mpo.gc.ca/csas-sccs/Publications/ResDocs-DocRech/2018/2018%5F059-eng.html.

Ryoichi, I. Fin whale vocalizations observed with ocean bottom seismometers of cabled observatories off east Japan Pacific Ocean. *Japanese Journal of Applied Physics*, 54(7S1), 06 2015. doi: 10.7567/JJAP.54.07HG03.

Shiu, Y., Palmer, K. J., Roch, M. A., Fleishman, E., Liu, X., Nosal, E.-M., Helble, T., Cholewiak, D., Gillespie, D., and Klinck, H. Deep neural networks for automated detection of marine mammal species. *The Journal of the Acoustical Society of America*, 10(1), 01 2020. doi: 10.1038/s41598-020-57549-y.

Simard, Y. and Roy, N. Une décennie de suivis acoustiques continus des rorquals bleus, des rorquals communs et du krill dans le parc marin du Saguenay–Saint-Laurent de 2007 à 2017. *Le Naturaliste canadien*, 142(2):106–114, June 2018. doi: 10.7202/1047152ar.

Simard, Y., N., R., Aulanier, F., and Giard, S. Blue whale continuous frequentations of St. Lawrence habitats from multi-year PAM series. *DFO Can. Sci. Advis. Sec. Res. Doc*, (2016/091):v–14, Oct. 2016. https://www.dfo-mpo.gc.ca/csas-sccs/Publications/ResDocs-DocRech/2016/2016%5F091-eng.html.

Simon, M., Stafford, K. M., Beedholm, K., Lee, C. M., and Madsen, P. T. Singing behavior of fin whales in the Davis Strait with implications for mating, migration and foraging. *The Journal of the Acoustical Society of America*, 128(5):3200–3210, Nov. 2010. doi: 10.1121/1.3495946.

Sourisseau, M., Simard, Y., and Saucier, F. J. Krill aggregation in the St. Lawrence system, and supply of krill to the whale feeding grounds in the estuary from the gulf. *Marine Ecology Progress Series*, 314:257–270, May 2006. doi: 10.3354/meps314257.

Stafford, K. M., Fox, C. G., and Clark, D. S. Long-range acoustic detection and localization of blue whale calls in the northeast Pacific Ocean. *The Journal of the Acoustical Society of America*, 104 (6):3616–3625, 12 1998. doi: 10.1121/1.423944.

Stafford, K. M., Mellinger, D. K., Moore, S. E., and Fox, C. G. Seasonal variability and detection range modeling of baleen whale calls in the Gulf of Alaska, 1999–2002. *The Journal of the Acoustical Society of America*, 122(6):3378–3390, Dec. 2007. doi: 10.1121/1.2799905.

Tary, J. B., Peirce, C., Hobbs, R. W., Bonilla Walker, F., De La Hoz, C., Bird, A., and Vargas, C. A. Application of a seismic network to baleen whale call detection and localization in the Panama basin–a Bryde's whale example. *The Journal of the Acoustical Society of America*, 155:2075–2086, 03 2024. doi: 10.1121/10.0025290.

Urrego-Blanco, J. and Sheng, J. Formation and distribution of sea ice in the Gulf of St. Lawrence: A process-oriented study using a coupled ocean-ice model. *Journal of Geophysical Research: Oceans*, 119(10):7099–7122, Sept. 2014. doi: 10.1002/2014JC010185.

Širović, A. and Oleson, E. M. *The Bioacoustics of Blue Whales–Global Diversity and Behavioral Variability in a Foraging Specialist. In: Clark, C.W., Garland, E.C. (eds) Ethology and Behavioral Ecology of Mysticetes*. Springer International Publishing, 2022. doi: 10.1007/978-3-030-98449-6_9.

Širović, A., Hildebrand, J., and Wiggins, S. Blue and fin whale call source levels and propagation range in the Southern Ocean. *The Journal of the Acoustical Society of America*, 122(2):1208–1215, 08 2007. doi: 10.1121/1.2749452.

Širović, A., Rice, A., Chou, E., Hildebrand, J., Wiggins, S., and Roch, M. Seven years of blue and fin whale call abundance in the Southern California Bight. *Endangered Species Research*, 28(1): 61–76, 2015. doi: 10.3354/esr00676.

Watkins, W., Daher, M., Repucci, G., George, J., Martin, D., DiMarzio, N., and Gannon, D. Seasonality and Distribution of Whale Calls in the North Pacific. *Oceanography*, 13(1), 2000. doi: 10.5670/oceanog.2000.54.

Weirathmueller, M. J., Stafford, K. M., Wilcock, W. S. D., Hilmo, R. S., Dziak, R. P., and Tréhu, A. M. Spatial and temporal trends in fin whale vocalizations recorded in the NE Pacific Ocean between 2003-2013. *PLOS ONE*, 12(10):1–24, 10 2017. doi: 10.1371/journal.pone.0186127.

Wilcock, W. S. D. Tracking fin whales in the northeast Pacific Ocean with a seafloor seismic network. *The Journal of the Acoustical Society of America*, 132(4):2408–2419, Oct. 2012. doi: 10.1121/1.4747017.

Zhong, M., Castellote, M., Dodhia, R., Lavista Ferres, J., Keogh, M., and Brewer, A. Deep Machine Learning Techniques for the Detection and Classification of Sperm Whale Bioacoustics. *The Journal of the Acoustical Society of America*, 147(3):1834–1841, 03 2020. doi: 10.1121/10.0000921.