Annual Report of Boundary Pass Acoustic Monitoring Year 1 (October 2018 - October 2019)

ECHO Program summary

The Vancouver Fraser Port Authority (VFPA)-led Enhancing Cetacean Habitat and Observation (ECHO) Program manages the analysis of a large underwater acoustic data set being acquired in Boundary Pass, off the southern coast of British Columbia. While a long-term station cabled to shore is being designed and constructed for the area, a series of Autonomous Multichannel Acoustic Recorders (AMARs) were deployed to operate continuously. Acoustic data from December 2018 to October 2019 were analyzed and are presented in the first annual Boundary Pass report.

What questions was the study trying to answer?

Analysis of the acoustic data sought to answer the following key questions:

- What are the long and short term trends in ambient noise levels at Boundary Pass?
- What are the source levels of different commercial vessels transiting Boundary Pass, and what is the associated range of source levels?
- Is Boundary Pass a suitable location for measuring the underwater noise levels of a majority of vessels transiting the area?
- What marine mammals can be detected in the area?

Who conducted the project?

JASCO Applied Sciences (Canada) Ltd. (JASCO) were retained by Transport Canada to install the Boundary Pass station, including the deployment of autonomous recorders until the cabled station is built. JASCO was also retained by the Vancouver Fraser Port Authority to conduct data analysis of ambient noise, vessel source levels and marine mammal detections.

What methods were used?

During the first year of the study, four deployments of AMARS were made, each lasting approximately 100 days. The AMARs recorded at 128,000 samples per second with a recording bandwidth of 10 Hz to 64 kHz.

Analysis of ambient noise was conducted using JASCO's PAMlab acoustic analysis software suite, which presented spectrograms, decade-band and 1/3-octave band level statistics, power spectral density percentiles, and plots of sound levels as a function of day of the week and hour of the day.

Vessel source levels were calculated using ShipSound, a component of JASCO's PortListen online noise measurement system. Additional data, including water current speed from an acoustic Doppler current profiler, Automatic Identification System (AIS) messages from vessels, and weather data were collected proximate to the station. All source level measurements were subject to a manual review.

An automated detector developed by JASCO was used to detect the vocalizations of killer whales, humpback whales and Pacific white-sided dolphins. All detections were manually verified by an experienced analyst.

What were the key findings?

Ambient Noise

- Fast currents (up to ~ 2 m/s) at the AMAR mooring locations in Boundary Pass, were found to create flow noise in the acoustic recordings. These effects were primarily detected in the 10-100 Hz frequency range when current speeds exceeded 0.5 m/s.
- During quiet times without vessels present, wind speeds greater than ~10 m/s were found to slightly increase sound levels above 100 Hz. This effect was greater in winter when wind speeds were higher.
- Vessel traffic presence, assessed using AIS records, led to substantial increases in ambient sound levels at all measured frequencies. Broadband levels increased by ~14 dB when AIS-tracked vessels were within 6 km of the hydrophones. Increases in sound levels in daytime hours during the summer months are likely attributed to the presence of small recreational boats.

Vessel source levels

- The Boundary Pass hydrophone locations were found to be suitable for processing vessel source levels for ships travelling in both the inbound and outbound international shipping lanes.
- A total of 6,140 vessel source level measurements were analyzed with JASCO's ShipSound application during this study period, of which 68% passed the manual quality control checks. This is a substantial increase in the rate of vessel source level measurements, compared to the former Strait of Georgia underwater listening station.
- Nearly half of all accepted measurements were for bulkers, while container ships accounted for approximately one quarter of the measurements during the study period. Container ships had the highest average radiated noise levels at ~192 dB, followed by bulkers and vehicle carriers at ~189 dB.

Marine Mammal Detections

- A total of 8,940 killer whale (any ecotype) vocalizations and 1,094 humpback whale vocalizations were reported by the automated detector during the study period. No Pacific white-sided dolphins were detected. Note that the number of detections is a count of vocalizations, and is not indicative of the number of animals present.
- Killer whales (any ecotype) were detected on 74 days over the study period, with the highest count in July 2019. Humpback whales were detected on 19 days.

Conclusions and next steps

The AMAR deployments in Boundary Pass indicate that this location is appropriate to maximize collection of accurate vessel source levels for vessels transiting both the inbound and outbound shipping lanes of Boundary Pass. This confirms the position is well suited for installation of the long-term cabled underwater listening station, scheduled for spring 2020. Bulkers and container ships constitute the majority of accepted source level measurements at Boundary Pass, with large containerships being the loudest vessel category measured.

Ambient noise levels in Boundary Pass are affected by current-induced water flow and mooring noise. On a seasonal basis, sound levels increase in winter due to high wind speeds, while short term (hourly) differences in sound level occur during the summer, likely due to recreational traffic. Detection of killer whale and humpback whale vocalizations at the AMARs will supplement the understanding of use of this area by whale species.

The AMARS will continue to be deployed for the continuous collection of acoustic data, until such time as the cabled station is installed. This report represents the first of several planned annual reports on ambient noise, vessel source levels and marine mammal detections for Boundary Pass.

Annual Report of Boundary Pass Acoustic Monitoring

Year 1, December 2018 to October 2019

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Disclaimer:

The results presented herein are relevant within the specific context described in this report. They could be misinterpreted if not considered in the light of all the information contained in this report. Accordingly, if information from this report is used in documents released to the public or to regulatory bodies, such documents must clearly cite the original report, which shall be made readily available to the recipients in integral and unedited form.

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Executive Summary

Vancouver Fraser Port Authority (VFPA) has entered an agreement with Transport Canada to manage the analysis of a large underwater acoustic dataset being acquired in Boundary Pass, British Columbia. VFPA has contracted JASCO Applied Sciences (JASCO) to perform the data analysis and reporting. This report discusses the data collection and provides the results of the analysis.

JASCO is also responsible for acquiring the acoustic data under a separate agreement with Transport Canada. The data acquisition started 12 Dec 2018 and will continue to at least 31 Mar 2023. Acoustic data are being acquired using autonomous multichannel acoustic recorders (AMAR) until a permanent cabled underwater acoustic listening station (ULS) can be deployed –tentatively scheduled for spring 2020. To date, five separate deployments of AMARs have been made, each lasting approximately 100 days. The first four deployments have already been retrieved and their data has been successfully downloaded. The fifth deployment was performed 31 Jan 2020 using an AMAR-G4 recorder that is expected to operate until early June 2020. Additional metadata are being collected, including water current speed from an acoustic doppler current profiler (ADCP), automatic identification system (AIS) messages from vessels, and wind speed and direction measurements from Environment Canada weather stations.

Acoustic data from 12 Dec 2018 to 15 Oct 2019 have been analyzed for ambient noise level statistics, marine mammal vocalizations, and vessel source levels which have been reported to the VFPA for their Enhancing Cetacean Habitat and Observations (ECHO) program. This report contains a summary of those results and investigates the effect of water currents, wind speed, and vessel traffic on sound levels, as well as the temporal variability of sound level statistics and the acoustic performance of the moorings. This is the first of several annual reports in support of the long-term Boundary Pass ULS monitoring program.

Water currents in Boundary Pass were often fast, reaching up to ~2 m/s or ~4 knots. These currents were found to create flow noise in the acoustic recordings primarily in the 10–100 Hz band when current speeds were greater than 0.5 m/s. Although the moorings for all AMARs used the same mooring design, some moorings were found to produce more mooring noise than others. This was discovered by analyzing long-term trends in ambient noise levels and by comparing sound levels during periods when two AMARs recorded simultaneously.

During relatively quiet times (when vessels were absent), sound levels between AMARs differed at frequencies at or below 400 Hz. During louder times (when vessels were present within 6 km of the hydrophone), sound levels between AMARs agreed well at frequencies above 30 Hz. This suggests the hydrophone calibrations were accurate but that mooring-generated noise varied between recorders. There is still some uncertainty as to why the quieter levels recorded by multiple AMARs differed. This could also be related to site-specific water currents (e.g., differences between currents at the individual AMAR locations or between the ADCP location and the AMAR locations). This variability is expected to be reduced once the cabled ULS is installed since it will use a rigid mooring, include an ADCP mounted to the ULS frame, and will be deployed for multiple years at a time. Nevertheless, the mooring noise is not an issue for ship sound emission measurements that are higher in amplitude.

During quiet times, wind speed was found to increase sound levels at frequencies above 100 Hz when the wind speed was greater than ~10 m/s. This effect was greater during winter months when seasonal wind speeds were higher.

Vessel traffic was found to substantially increase sound levels at all frequencies (up to 64 kHz). Median broadband sound levels increased by ~14 dB when AIS-tracked vessels were within 6 km of the hydrophone. The increases were largest in the 10–100 Hz, 100–1000 Hz, and 1–10 kHz bands. The higher frequency 10–64 kHz band also increased substantially for the 95th percentile (L_5 exceedance percentile).

Over 10000 manually-validated marine mammal detections were found in the acoustic data for the ~10 month study period. Most (89%) of these were from killer whales, and the detections occurred throughout all months of the study period. The remaining detections were from humpback whales, which were found in all seasons but not all months. No Pacific white-sided dolphin vocalizations or fish sounds were detected in the recordings.

Over 6000 vessel source level measurements were analyzed with JASCO's ShipSound application. A large fraction of these measurements were of bulker and container ships, but also included many vehicle carriers, cruise ships and tugs. The hydrophone location was suitable for processing source level measurements for vessels travelling in both the inbound and outbound international shipping lanes and provided a higher rate of vessel source level measurements than the former Strait of Georgia ULS.

1. Introduction

Underwater acoustic data have been collected continuously in Boundary Pass since December 2018 as part of a long-term measurement program for Transport Canada. The measurement program began with deployments of JASCO's calibrated Autonomous Multichannel Acoustic Recorders (AMAR-G3) as a temporary method of collecting acoustic data until a cabled real-time underwater listening station (ULS) can be deployed. Water current speed, wind speed, and vessel traffic data have also been collected as part of this measurement program to assist with interpretation. Figure 1 shows a map of the instrument locations.

Vancouver Fraser Port Authority (VFPA) has commissioned JASCO to analyze the underwater sound recordings as part of VFPA's Enhancing Cetacean Habitat and Observations (ECHO) program. The analysis is an ongoing effort that has been occurring after each servicing trip of the AMARs, approximately every 3.3 months. The ongoing analysis includes:

- Ambient noise statistics,
- Detection and manual validation of marine mammal vocalizations, and
- ANSI 12.64-2009 (R2014) vessel source levels (including radiated noise levels and monopole source levels).

Acoustic data from Dec 2018 to Oct 2019, corresponding to the first three deployments, has been analyzed and reported for ambient noise statistics (Grooms and Warner 2019a, 2019b) and marine mammal vocalizations (Frouin-Mouy 2019a, 2019b). Vessel source level measurements from the same period have been analyzed and are accessible through ShipSound, a component of JASCO's online PortListen® noise measurement system.

This report contains a comprehensive analysis of these previously reported ambient noise and marine mammal detection results from the first year of measurements (Deployments 1–3, 12 Dec 2018 to 15 Oct 2019). Acoustic data from the next 4-month deployment period (Oct 2019 to Jan 2020) will be analyzed and presented in a future report.

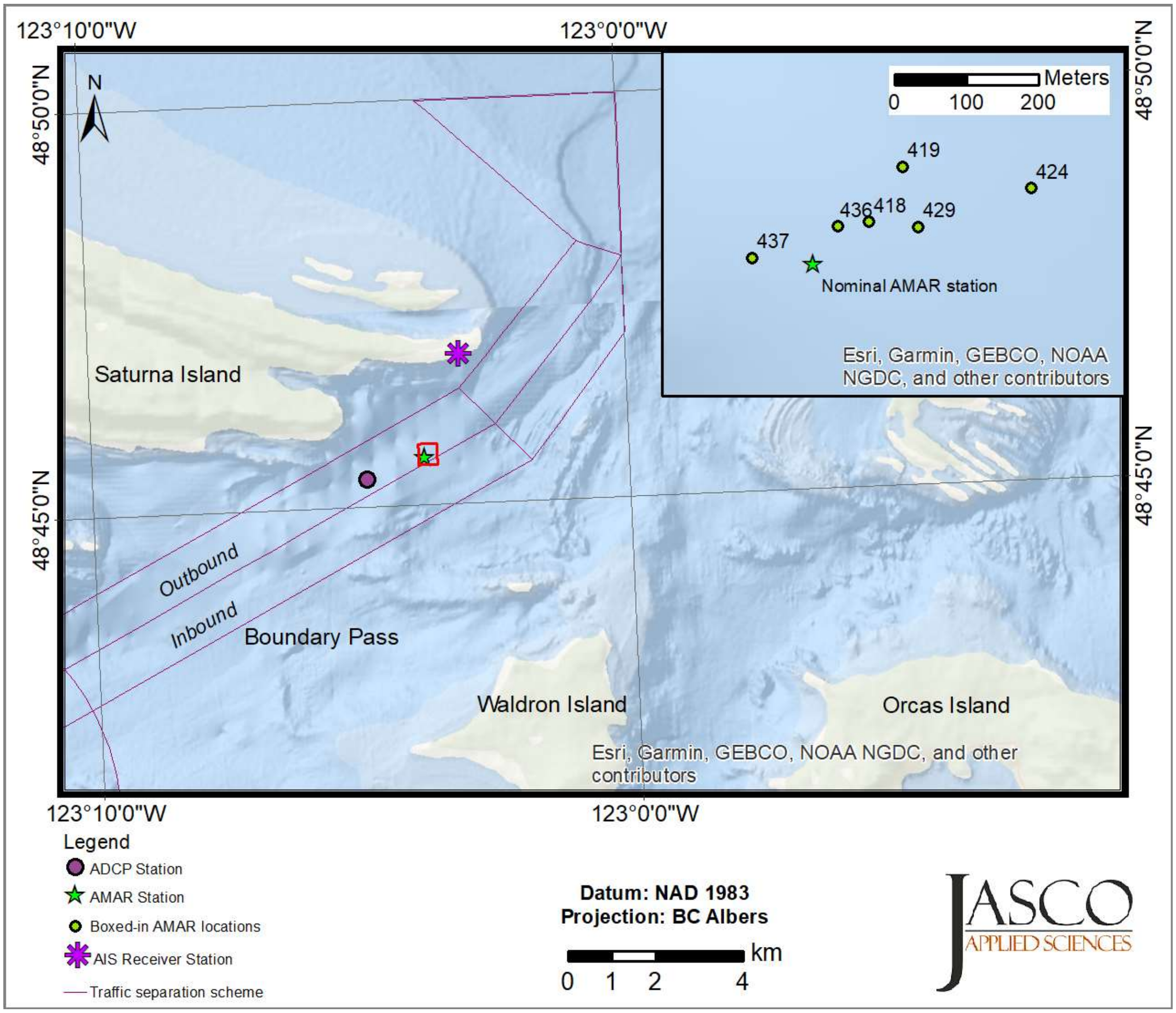


Figure 1. Map showing the locations the AMAR and ADCP stations, and the Automatic Identification System (AIS) receiver. The accurate (triangulated) AMAR deployment locations of each AMAR deployed during the analysis period are shown on the inset map and are labelled with the AMAR's serial number. The vessel lane separation paths are shown as purple lines.

2. Methods

2.1. Data Acquisition

2.1.1. Acoustic Measurements

Underwater sound was recorded with Autonomous Multichannel Acoustic Recorders-Generation 3 (AMARs, JASCO), deployed on sub-sea moorings between the international shipping lanes in Boundary Pass (see map in Figure 1). The AMAR moorings incorporated backup retrieval measures, including tandem acoustic releases and satellite beacons, to reduce the likelihood of equipment loss (Figure 2).

Each AMAR was equipped with an M36-V35 omnidirectional hydrophone (GeoSpectrum Technologies Inc., −165 ± 3 dB re 1 V/µPa nominal sensitivity). The AMAR hydrophones were protected by a hydrophone cage, which was covered with a shroud to minimize noise artifacts from water flow. The AMARs recorded at 128 000 samples per second (10 Hz to 64 kHz recording bandwidth) with 24-bit resolution, 1.8 TB storage memory, and 6 dB gain. Figure 3 shows an AMAR mooring on the aft deck of the *RV Richardson Point* and the mooring being towed behind the vessel during deployment.

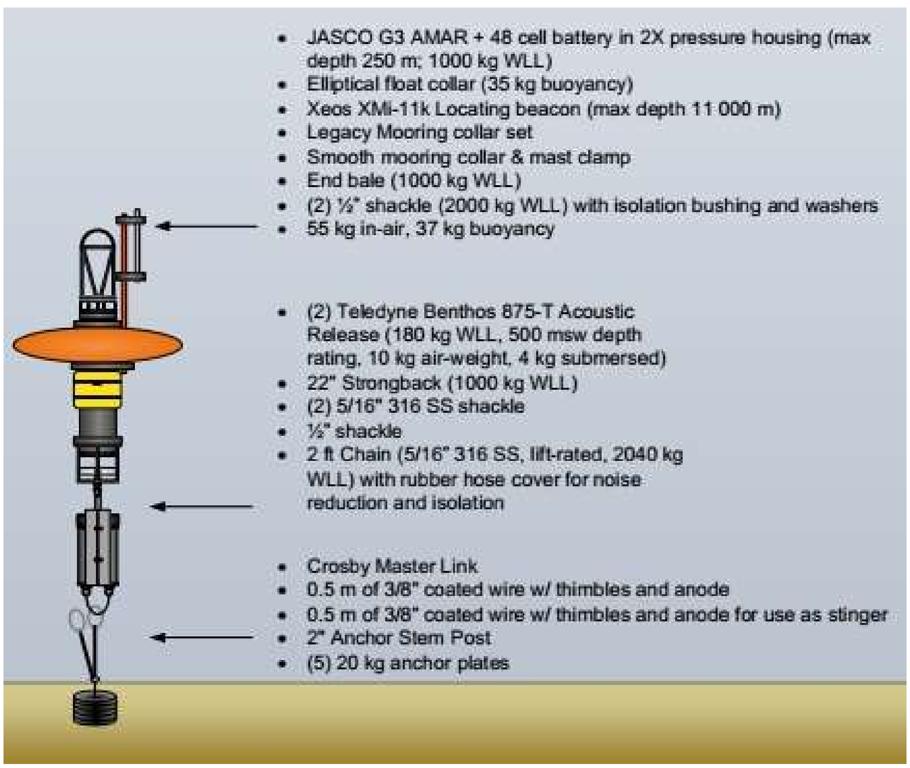


Figure 2. Boundary Pass Underwater Listening Station (ULS) mooring (JASCO design 202). The hydrophone was located a few metres above the seabed, inside the protective cage at the top of the AMAR.

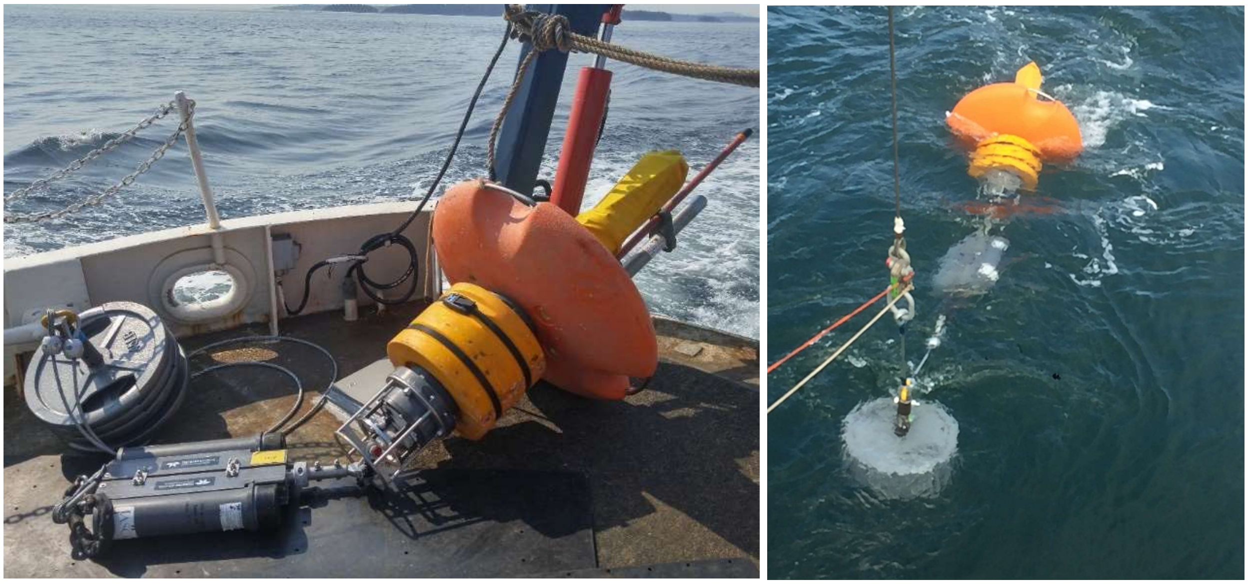


Figure 3. AMAR mooring (left) on the back deck of the *RV Richardson Point* ready for deployment and (right) being towed slowly to the deployment location.

Immediately upon deploying each AMAR mooring, a GPS measurement was taken to record the tentative AMAR deployment position. Water currents, however, caused the AMAR to drift horizontally as the mooring descended to the seafloor. The recorders were accurately localized on the seabed by acquiring ranges to the acoustic releases at four locations and triangulating. The estimated easting and northing accuracy after localization was approximately 2.4 m.

During each deployment trip, two AMARs were deployed within a couple hundred metres of each other. For Deployments 1 and 2, one AMAR started recording immediately, and the other was programmed to start recording close to the time when the first AMAR would fill its memory. For Deployment 3, the AMARs recorded alternating 25-hour periods (Figure 4). This recording schedule was implemented to improve recorder redundancy throughout the ECHO program’s 2019 Haro Strait and Boundary Pass voluntary vessel slowdown trial, which began on 5 July 2019. Table 1 lists the deployment locations and recording periods of each AMAR. The deployment locations are also shown in Figure 1.

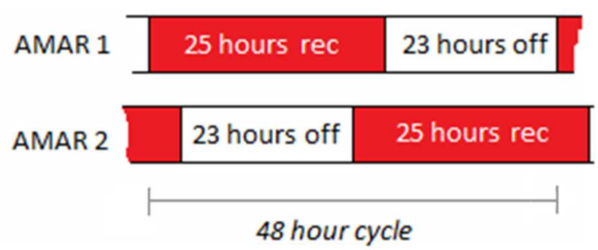


Figure 4. Recording schedule configuration for AMARs during Deployment 3.

Table 1. Triangulated AMAR recorder locations and periods used for analysis for each deployment. AMAR 437, 418, and 429 data were used during time periods when two AMARs recorded simultaneously, because they had lower mooring noise. Deployment 1 and 2 AMARs recorded continuously between their start and end dates. Deployment 3 AMARs recorded for 25 hours and then were inactive for 23 hours, with recording cycle start times staggered by 24 hours to obtain one hour per day of overlap between the two AMARs. The recorder locations are also shown in Figure 1.

Deployment	AMAR SN	Latitude (N)	Longitude (W)	Water Depth (m)	Start Date/Time	End Date/Time	Hydrophone height above seafloor (m)
1	437	48° 45.60665'	123° 3.86085'	197	2018-12-12 22:32	2019-02-07 16:42	5.3
	436	48° 45.63044'	123° 3.79622'	199	2019-01-23 00:00	2019-03-20 18:21	
2	418	48° 45.63369'	123° 3.77304'	197	2019-03-21 14:24	2019-05-17 07:31	3.6
	419	48° 45.67526'	123° 3.74762'	196	2019-05-08 00:00	2019-07-03 18:03	
3	424	48° 45.65912'	123° 3.65126'	195	2019-07-03 23:00	2019-10-15 23:14	3.3
	429	48° 45.62993'	123° 3.73605'	194	2019-07-04 00:00	2019-10-15 01:00	

The laboratory calibrations of the AMARs at a single frequency were verified to within 0.5 dB before deployment and after retrieval using a Pistonphone Type 42AA precision sound source (G.R.A.S. Sound & Vibration A/S). The pistonphone calibrator produces a constant tone at 250 Hz at the hydrophone sensor. The level at which the AMAR records the reference tone yields the total pressure sensitivity for the instrument, i.e., the conversion factor between digital units and pressure. Verifying calibrations before and after deployment ensured that the sensitivity of the hydrophone did not change over the deployment period.

2.1.2. Water Current Measurements

Water current speed and direction, as functions of depth, were recorded with a Workhorse Sentinel 300 kHz Acoustic Doppler Current Profiler (ADCP, Teledyne), deployed on sub-sea moorings between 5 and 10 m above the seafloor and approximately 1.5 km southwest of the AMARs (Figure 1). This location was chosen because it was far enough from the AMARs that the acoustic energy from the ADCP would not contaminate the AMAR recordings, and because the water depth was shallow enough (approximately 100 m) that the upward-facing 300 kHz ADCP could measure near-surface currents. The ADCP moorings incorporated backup retrieval measures, including tandem acoustic releases and satellite beacons, to reduce the likelihood of equipment loss (Figure 5).

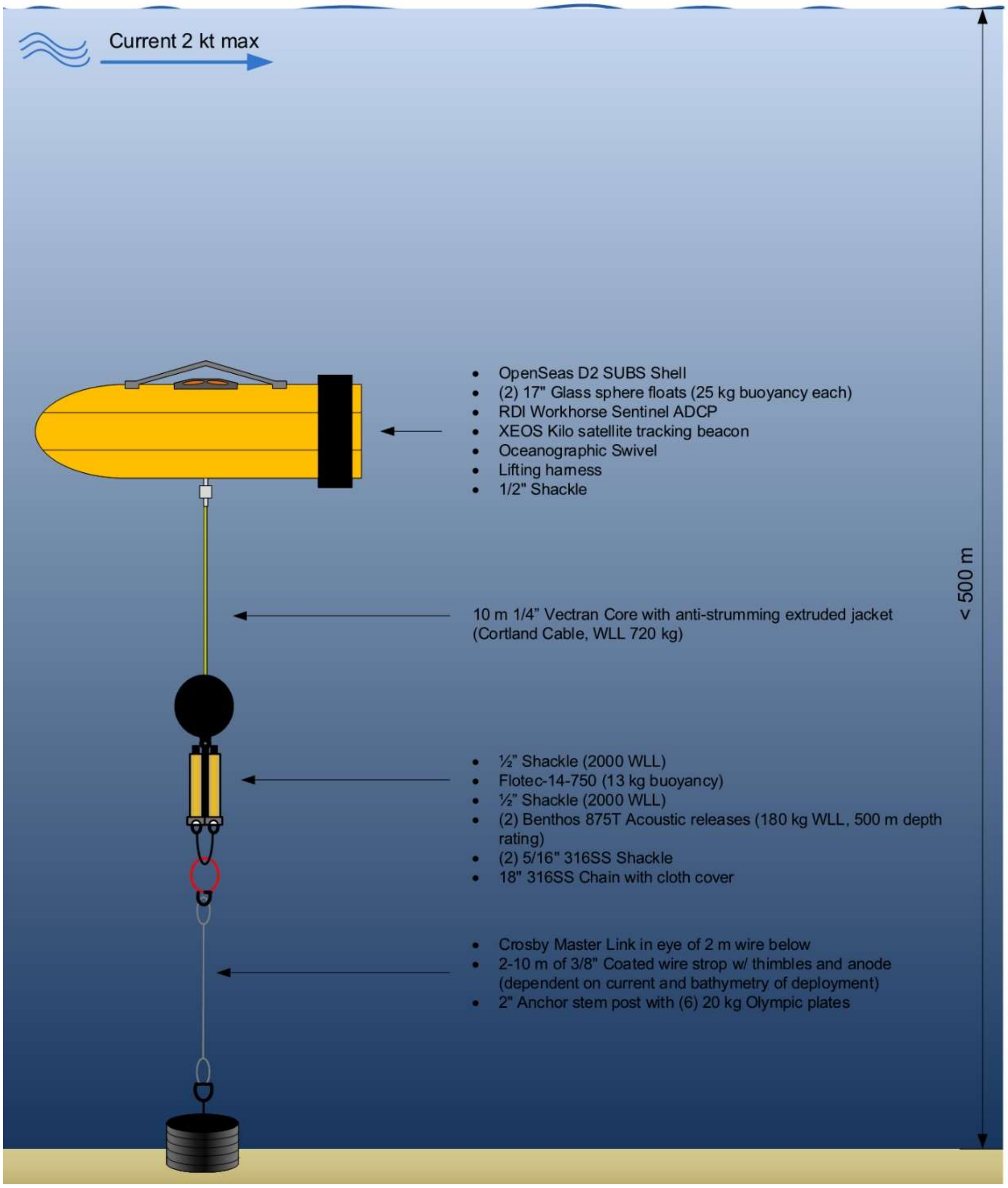


Figure 5. ADCP mooring used for the three deployments (JASCO design 139). The ADCP was deployed between 5 and 10 m above the seafloor.

The ADCPs were configured to measure current profiles every 12 seconds (ping) and record averaged measurements over 50 pings (i.e., 10 minutes). Spline interpolation was used to predict current speeds from the recorded 10-minute resolution to the 1-minute resolution of the processed acoustic data. The ADCP provided current speed and direction over the water column in 5-m depth bins. Upward-facing ADCPs cannot measure currents at very shallow depths, so the measurements in the top ~15 m of the water column are not reliable.

Table 2 lists the ADCP recorder locations and recording periods. The ADCP from the Deployment 1 stopped recording much earlier than anticipated, and the data were not usable. The WebTide Tidal

Prediction Model (v0.7.1) (Foreman et al. 2000, Institute of Ocean Sciences 2015) was used to fill the data gap for Deployment 1.

Table 2. ADCP recorder locations and recording periods. ADCP 11346 stopped recording early, and the data were not usable.

Deployment	ADCP SN	Latitude (N)	Longitude (W)	Water Depth (m)	Start Date/Time	End Date/Time
1	11346	48° 45.37719'	123° 4.81878'	99	2018-12-12 20:06	2018-12-31 21:46
2	11402	48° 45.46140'	123° 4.77384'	110	2019-03-21 23:10	2019-07-22 15:30
3	24715	48° 45.40152'	123° 4.77402'	99	2019-07-22 16:15	2019-10-15 16:45

2.1.3. Vessel Traffic Logging

Automatic Identification System (AIS) data were acquired by an on-shore recording station on Saturna Island (Figure 1). This system logged AIS data during the majority of the study period but was interrupted by power outages lasting several hours or days. AIS data from MarineTraffic.com were purchased to fill in these data gaps.

The AIS data is a reliable source of traffic information for large vessels. Small vessels are not required to transmit AIS data, but some choose to do so for traffic safety reasons. AIS vessel traffic data, therefore, represents only a portion of the overall vessel traffic.

2.1.4. Wind Speed Measurements

Hourly wind speed measurements from Environment Canada were downloaded to investigate the effect of wind speed on sound levels. Wind speed measurements were obtained from the Saturna Island CS weather station, located at East Point on Saturna Island, approximately 3 km from the AMARs. Wind speed measurements from the Kelp Reefs weather station, located in Haro Strait approximately 27 km from the AMARs, were used for times when the Saturna Island CS weather station data were unavailable.

2.2. Data Analysis

2.2.1. Ambient Noise Analysis

Analysis of ambient noise was conducted using JASCO's PAMlab acoustic analysis software suite. The initial ambient noise reports presented spectrograms, decade-band and decidecade- (or 1/3-octave) band level statistics, power spectral density percentiles, and plots of sound levels as a function of day of the week and hour of the day (Grooms and Warner 2019a, 2019b). This initial analysis was conducted for all recorded acoustic data grouped by synodic lunar month periods (29 days, 12 hours, and 44 minutes). An example ambient noise analysis report for one synodic month, which includes the data analysis methods, is presented in Appendix A.

The ambient noise analysis in the present report summarizes the results from the initial reports and also investigates the effects of other influential factors including currents, vessel presence, wind speed, and mooring noise.

2.2.2. Marine Mammal Detections

Killer whale, humpback whale, and Pacific white-sided dolphin vocalizations were automatically detected in all collected acoustic data using JASCO's PAMlab software suite, which has customized detectors for each species and call type.[1] The killer whale detector did not differentiate between different populations of killer whales (e.g., Southern Resident or Biggs killer whales). All detections were manually verified by an experienced analyst, and false detections were identified and discarded. The verified marine mammal detection results were presented in reports by synodic month (Frouin-Mouy 2019a, 2019b). An example marine mammal detection report, which describes the detection algorithms, is presented in Appendix B. The present report summarizes the verified marine mammal detection results for Year 1 (Deployments 1–3).

2.2.3. Vessel Source Levels

Vessel source levels were calculated using ShipSound, a component of JASCO's PortListen® online noise measurement system. The methods are fully described in Appendix C. The analysis for this report consists of a summary of the number of measurements that passed the quality control checks described in Appendix C.

[1] A fish-sound detector was also used but no validated fish sounds were identified in the recordings.

3. Results

The following subsections present ambient noise results, marine mammal detection results, and a summary of vessel source level measurements during the analysis period spanning Deployments 1–3 (Year 1, 12 Dec 2018 to 15 Oct 2019).

3.1. Ambient Noise Results

3.1.1. Influence of Water Currents

Water currents were measured primarily using an ADCP; however, for Deployment 1 (Dec 2018 to Mar 2019), the ADCP did not record valid data. For this period, current data were obtained from the WebTide model (see Section 2.1.2). In order to assess the accuracy of the WebTide model, we compared WebTide predictions with concurrent ADCP measurements.

The WebTide model is depth independent, whereas the ADCP measured depth-dependent currents. We calculated the correlation coefficient between the WebTide modelled currents and the ADCP measured currents at each depth, for the East-West and North-South components, as well as for the overall current speed magnitude. The highest correlation between the WebTide model and ADCP measurements occurred between 20 and 30 m depth, which indicates that the WebTide model was more representative of near-surface currents than of near-seafloor currents at this location (Figure 6).

Sound levels are affected by noise artifacts from current flow around the hydrophones. The hydrophones were deployed near the seabed where the correlation between WebTide and ADCP measurements was worse. Figure 7 shows an example of currents from the two data sources for a 24-hour period, and Figure 8 shows a 2-D histogram of the current speeds from all available measurements, where the ADCP measurements are from the first (deepest) depth bin. In general, the WebTide model agreed well with the broad temporal pattern of the measured currents but often overestimated the near-seafloor currents.

Figure 9 shows a histogram of the seafloor current speed from all available ADCP measurements during the analysis period (i.e., during Deployments 2 and 3). The seafloor current speed was taken from the current speed measured in the first depth bin, which was the closest bin to the seafloor. The maximum recorded current was 2.1 m/s (4.1 knots).

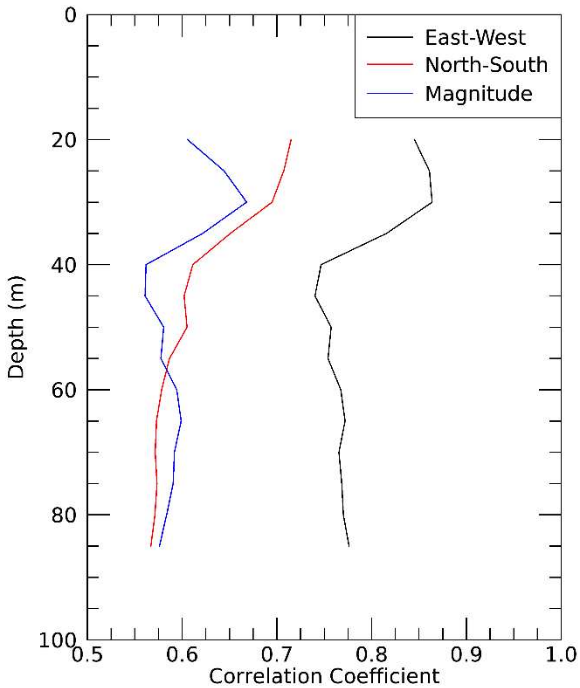


Figure 6. Current correlation coefficient profiles for WebTide model vs. depth-dependent ADCP measurements for Deployments 2 and 3. Correlation coefficients were calculated for the East-West and North-South components, as well as for the overall current speed magnitude. A correlation coefficient of 1.0 indicates perfect agreement.

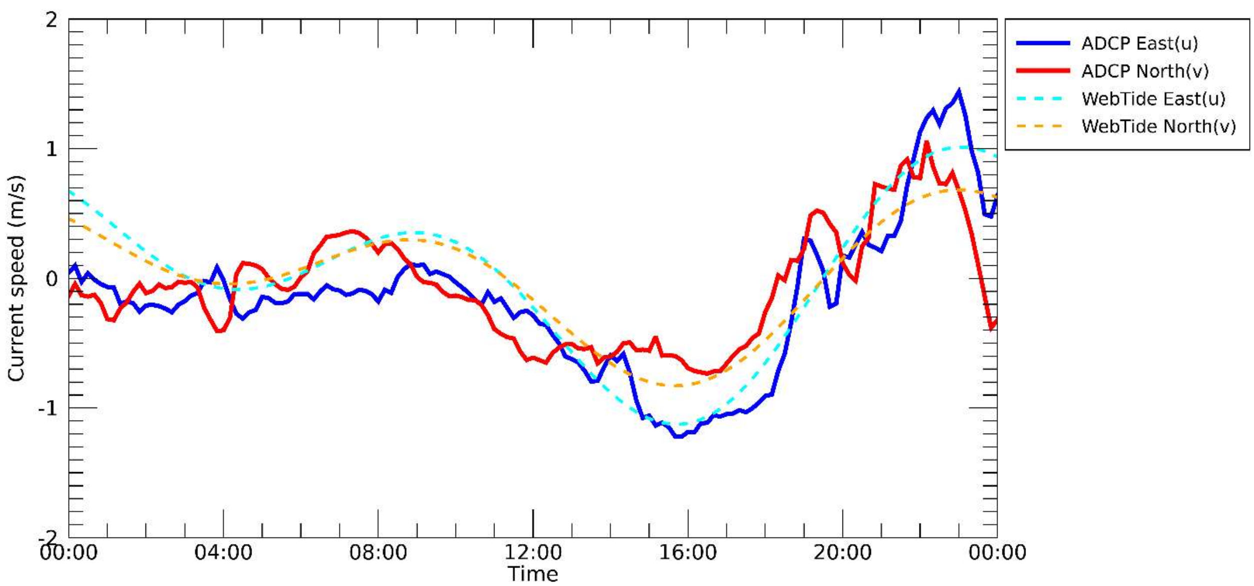


Figure 7. Current speeds from WebTide predictions and near-seafloor ADCP measurements on July 1, 2019 (during Deployment 2).

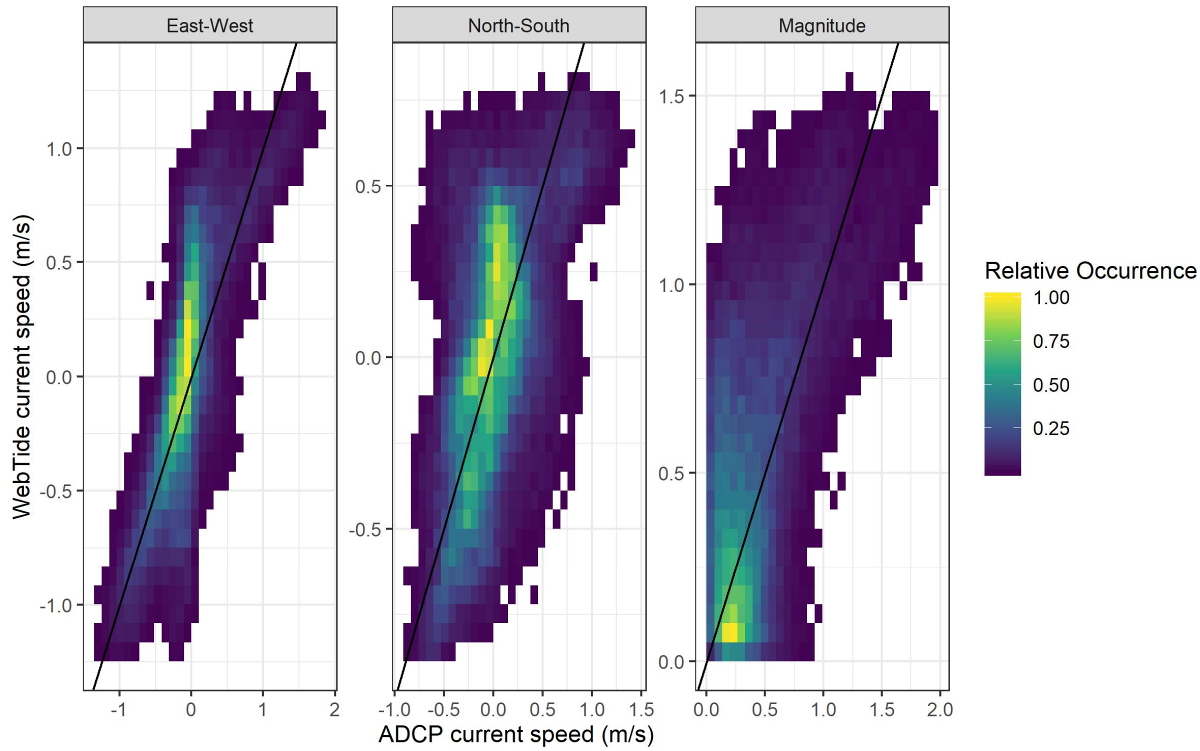


Figure 8. Two-dimensional histograms of current speeds for WebTide predictions and all near-seafloor ADCP measurements (Deployments 2 and 3) in the east-west direction, north-south direction, and the overall current speed magnitude. Black lines indicate where perfect agreement between data sources would occur. Probability scale has been normalized in each panel.

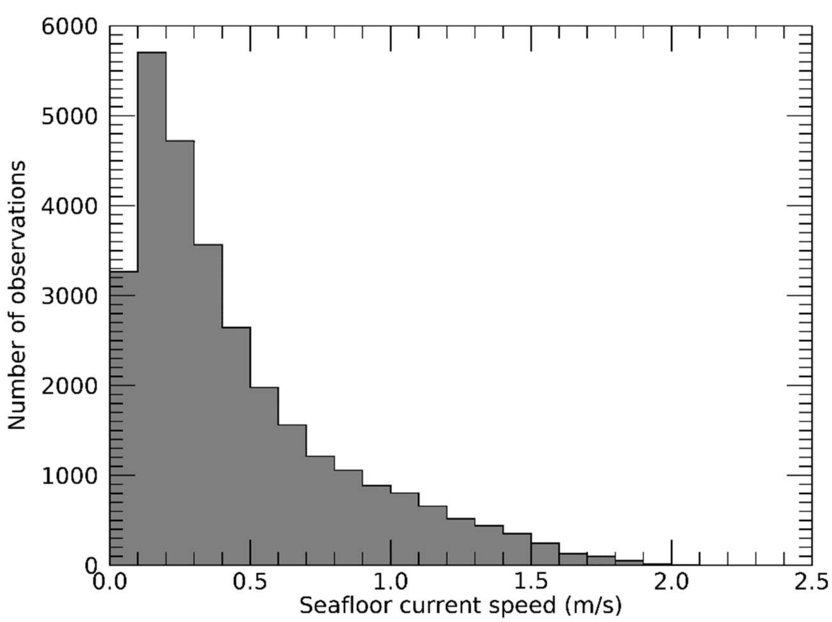


Figure 9. Histogram of seafloor current speed magnitude from all available ADCP measurements during the analysis period (Deployments 2 and 3). ADCP measurements were made every 10 minutes.

The effects of water current speed (as measured by ADCP near the seafloor) on sound levels are shown with a 2-dimensional (2-D) histogram of SPL (1-minute average) for each decade band (Figure 10). The effect of current speed is strongest in the 10-100 Hz band (top left plot of Figure 10) when the current speed exceeds approximately 0.5 m/s. There are relatively few measurements at these higher current speeds, however, so the trend is difficult to see. To reveal the trends at higher current speeds, the same data were normalized by the total number of counts at a given speed (Figure 11). For current speeds above 0.5 m/s, the 10-100 Hz band SPL increased by approximately 23 dB per m/s of current speed. This trend is weaker than the trend observed for the Strait of Georgia ULS, for which SPL increased by ~55 dB per m/s in that decade band (Warner et al. 2019). These differences are likely due to the different mooring designs: the Strait of Georgia ULS used a rigid mooring whereas the Boundary Pass moorings used buoyant components that could move with the currents. There is also potential that the near-seafloor currents measured at the ADCP location are not representative of the near-seafloor currents at the AMAR locations. The ADCP was deployed approximately 1.5 km from the AMARs (to prevent their pings from contaminating the acoustic data), and the water depth was half as deep at the ADCP (~100 m depth) than at the AMAR locations (~200 m depth). The WebTide model predicts lower current speeds at the AMAR locations, which suggests that the ~23 dB of flow noise per m/s of current may be underestimated here.

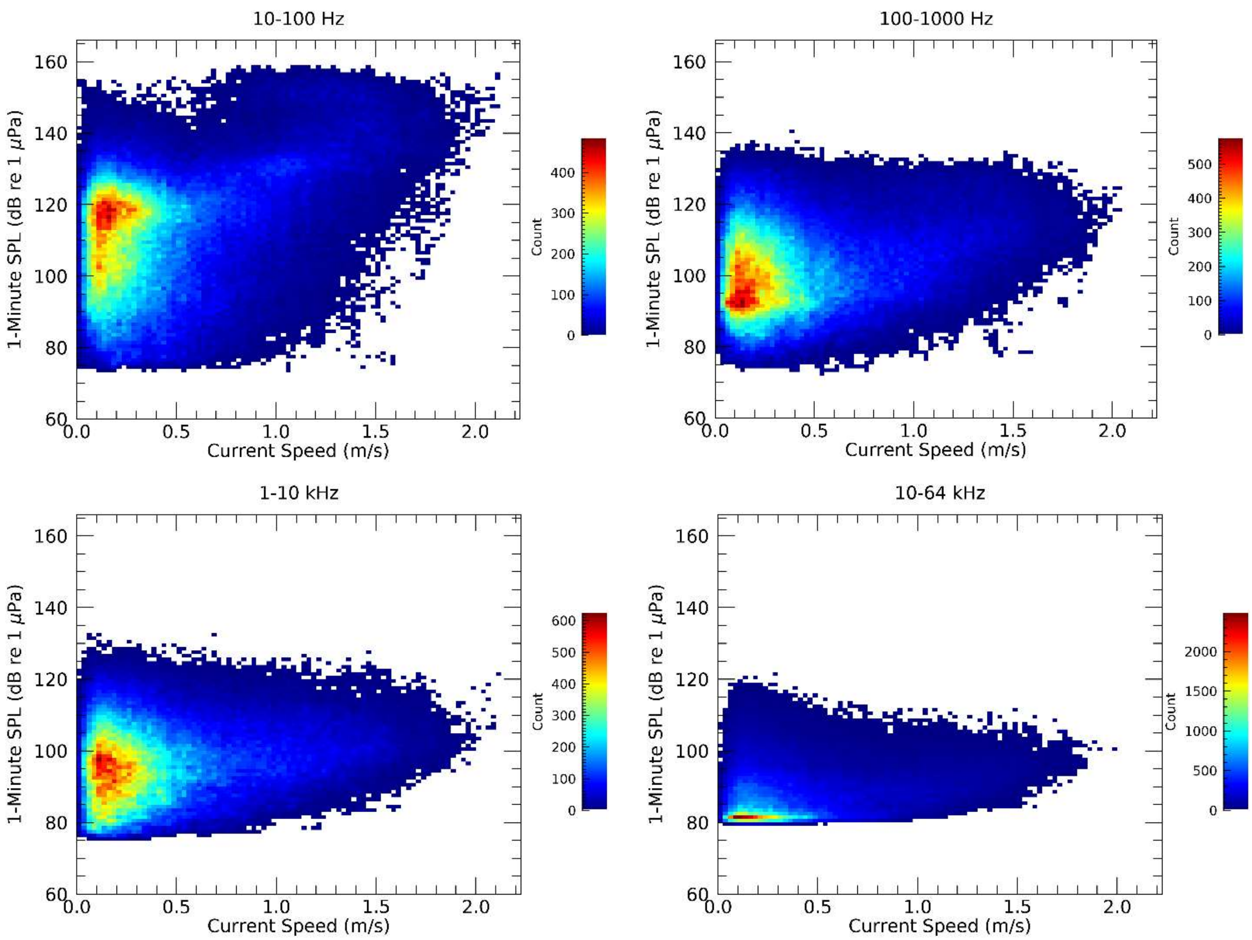


Figure 10. Two-dimensional histograms by decade band of 1-minute averaged SPL vs. ADCP-measured seafloor current speed for Deployments 2 and 3.

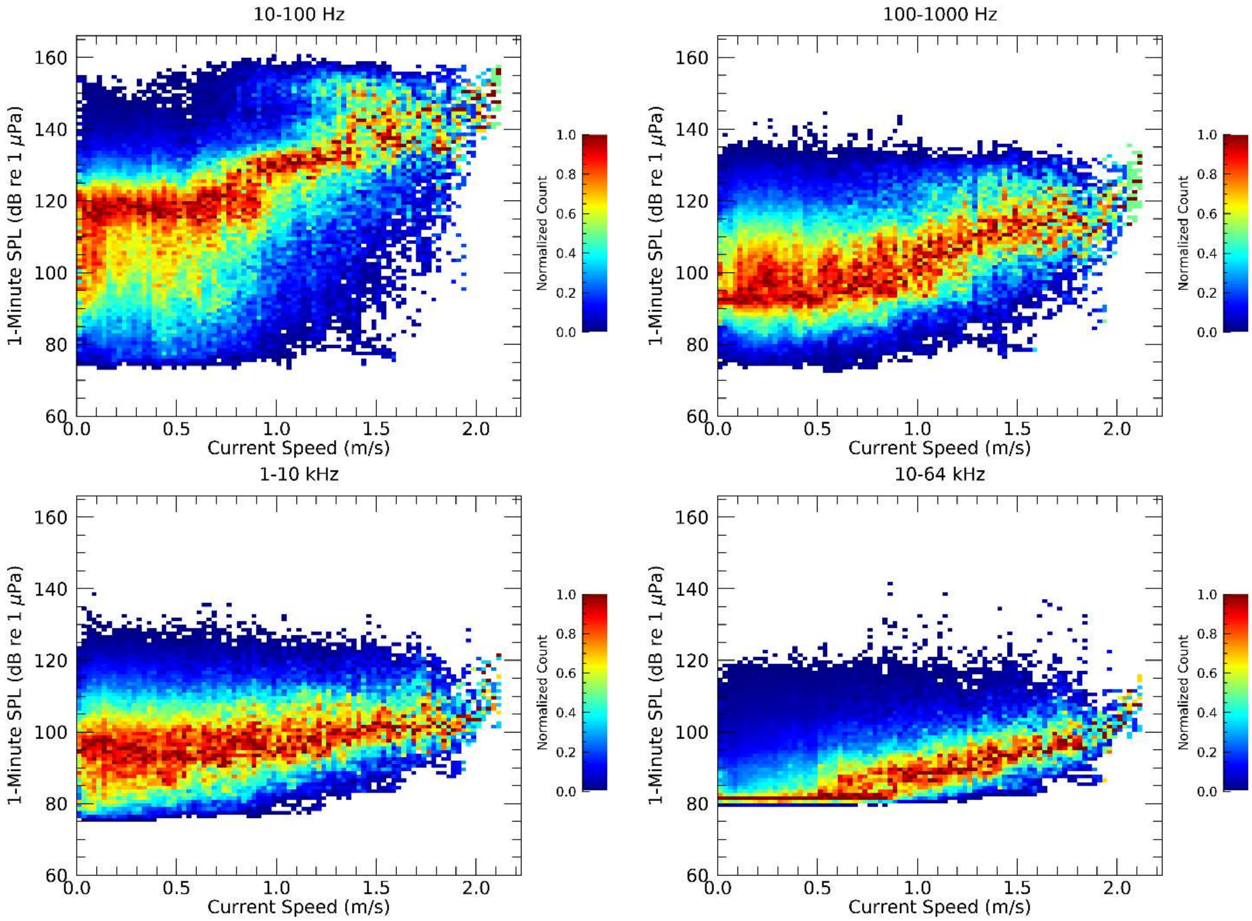


Figure 11. Two-dimensional normalized histograms by decade band of 1-minute averaged SPL vs. ADCP-measured seafloor current speed for Deployments 2 and 3. This figure presents the same data as shown in Figure 10, but the counts for each SPL-current bin have been normalized (divided by) the maximum count within the corresponding current speed interval.

3.1.2. Influence of Wind Speed

Figure 12 shows the histogram of wind speed, and Figure 13 shows a box-and-whisker plot of the wind speeds by month, during the analysis period (Deployments 1–3; the plot format is explained in detail in the Glossary). Wind speeds were generally higher in winter.

Figure 14 shows two-dimensional histograms of SPL vs. wind speed in four frequency bands. The plots also show the 10th percentile levels in each wind speed bin and the expected wind-driven ambient noise levels based on the Knudsen curves (Knudsen et al. 1948). There does not appear to be an effect of wind speed on the 10–100 Hz sound levels. For the higher frequency bands, however, wind speed appears to influence the lower sound levels during periods of high wind speeds (greater than at least 10 m/s).

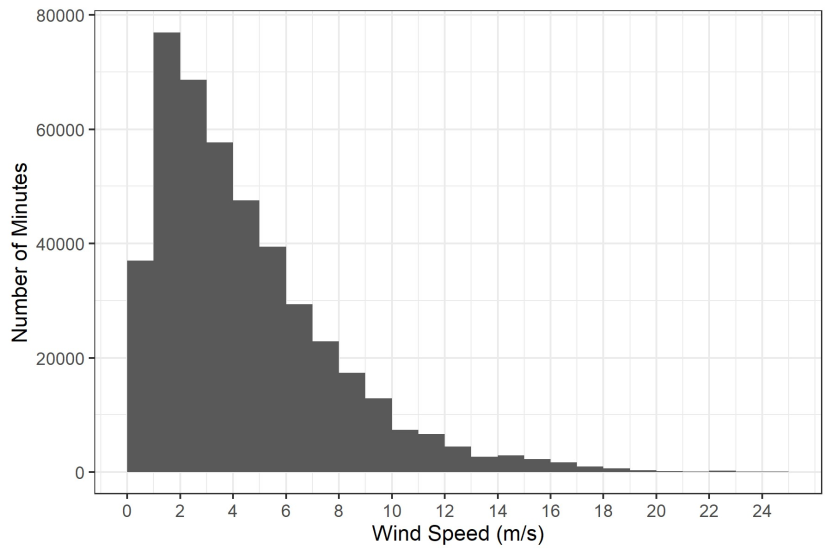


Figure 12. Histogram of wind speed during the analysis period (Deployments 1–3). Wind speed was linearly interpolated from hourly measurements to 1-minute intervals.

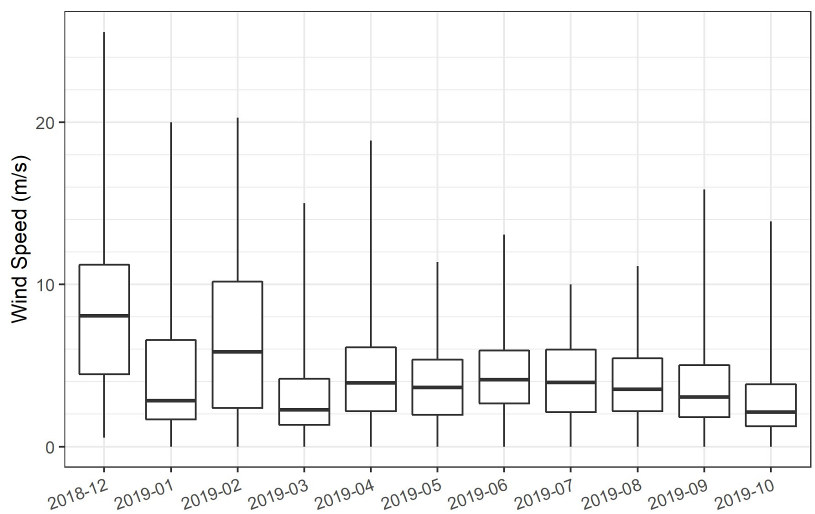


Figure 13. Box-and-whisker plot of wind speed as a function of month during the analysis period (Deployments 1–3). Wind speed was linearly interpolated from hourly measurements to 1-minute intervals. The box edges represent the 25th and 75th percentiles, the horizontal line within the box represents the median (50th percentile), and the whiskers show the highest and lowest observations.

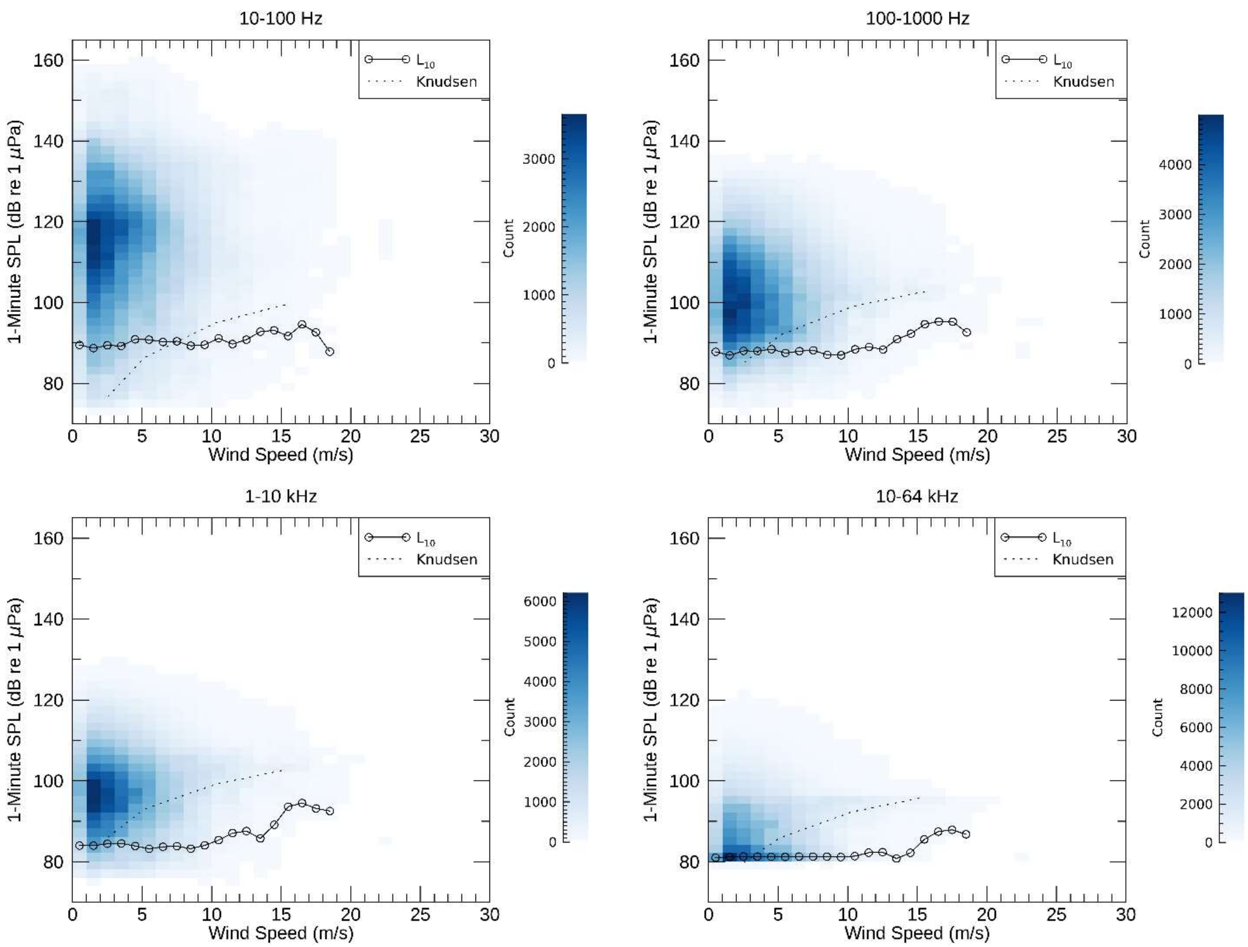


Figure 14. Two-dimensional histograms of decade-band SPL vs. wind speed in decade bands during the analysis period (Deployments 1–3). The lower 10th percentile of hourly SPL (L_{10}) within each wind speed bin is shown with a solid black and circled line (where there are at least 500 SPL measurements in the wind speed bin). The predicted sound levels from Knudsen et al. (1948) are shown as a dotted line.

3.1.3. Influence of Vessel Traffic

Vessel traffic (as determined from AIS) substantially increased sound levels in Boundary Pass across a wide frequency range. To assess the influence of AIS vessel traffic on sound levels, we investigated time periods with and without AIS-broadcasting vessels within 6 km of the hydrophone. For this analysis, we also filtered out time periods when seafloor current speeds exceeded 0.5 m/s to reduce the effect of current-induced flow noise (see Section 3.1.1). Figure 15 shows cumulative distribution functions for broadband and decade-band SPL for time periods with and without AIS-broadcasting vessels. Sound levels in all frequency bands increased by several dB due to vessel presence (Table 3). The increase in sound levels for the 10-64 kHz band during quiet times was likely underestimated because the noise floor of the hydrophones limited the ability to quantify low levels of high-frequency sounds.

Broadband sound levels were strongly correlated with the distance to the nearest AIS-broadcasting vessel. Figure 16 shows a 2-D histogram of sound levels vs. distance. The sound levels decayed at a rate approximately equal to spherical spreading (i.e., $20 \times \log_{10} r$, where r is the range to the nearest AIS vessel in metres). The trend at longer ranges is less clear, which is likely due to non-AIS vessel presence and because there is more opportunity for environmental factors (e.g., sound speed profile) to influence propagation loss.

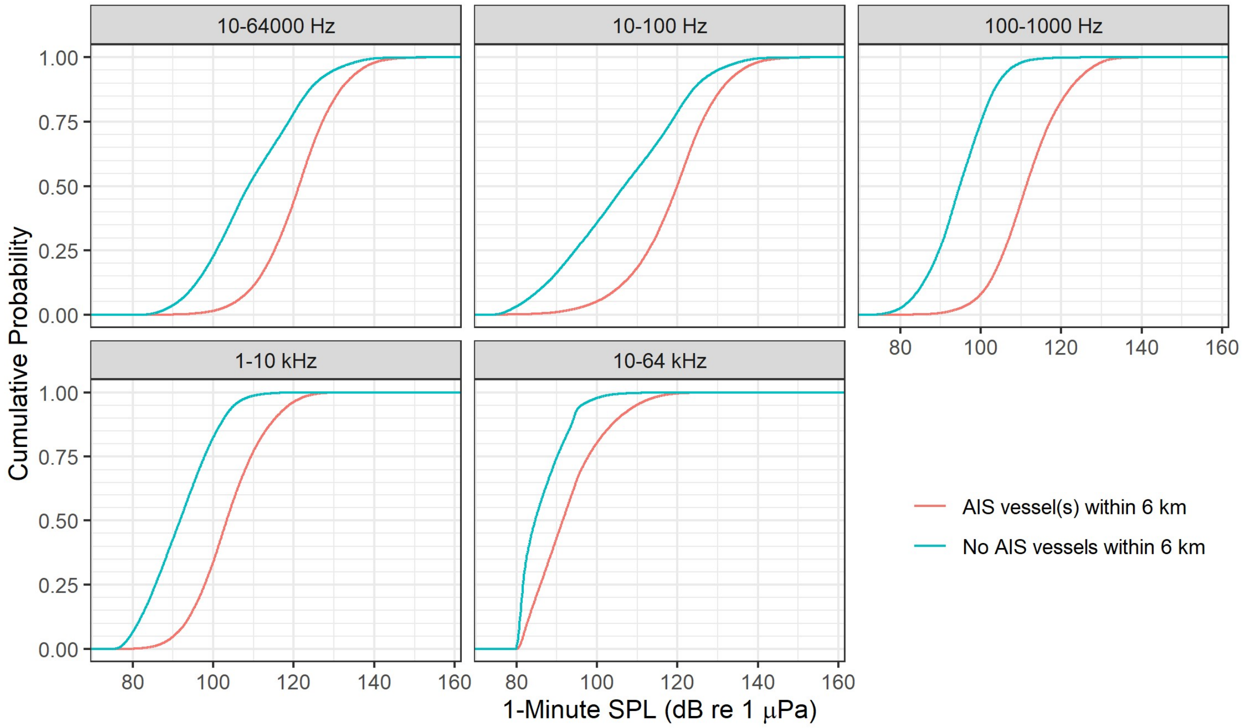


Figure 15. CDFs for periods with and without AIS vessel traffic within 6 km of the hydrophone in broadband and decade bands during the analysis period (Deployments 1–3). Time periods when seafloor current speed exceeded 0.5 m/s were excluded before calculating the CDFs. Table 3 lists the differences in percentiles and the L_{eq}.

Table 3. Increases in sound levels due to AIS vessel presence within 6 km of the hydrophone for different frequency bands during the analysis period (Deployments 1–3). Differences were calculated for time periods when seafloor current speed was less than 0.5 m/s.

Band (Hz)	Increase in SPL due to AIS vessel presence (dB)					
	L_{95}	L_{75}	L_{50}	L_{25}	L_{5}	L_{eq}
10–64000	14.4	14.5	13.5	11.4	7.9	6.1
10–100	18.3	18.4	14.5	10.8	7.3	5.6
100–1000	15.8	16.1	16.4	17.0	19.6	17.7
1000–10000	10.7	12.2	11.6	11.5	13.5	12.2
10000–64000	1.2	4.3	6.8	7.7	13.6	11.0

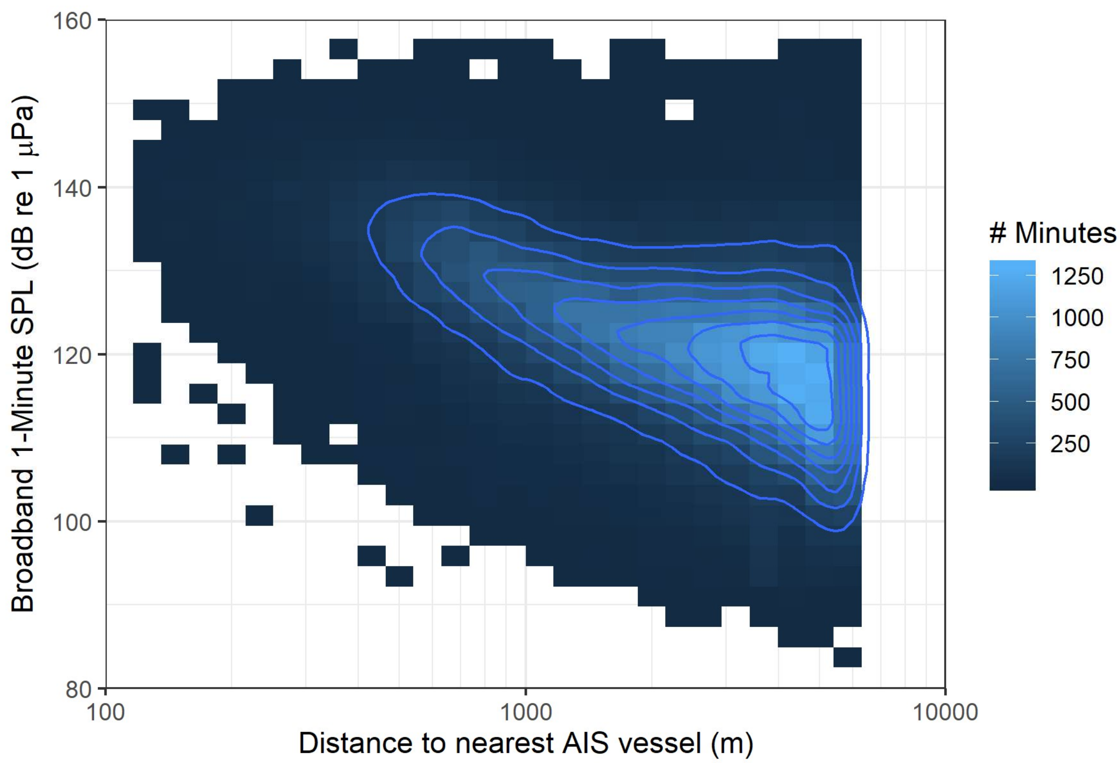


Figure 16. Broadband (10 Hz to 64 kHz) SPL vs. horizontal distance to the nearest AIS vessel during the analysis period (Deployments 1–3).

3.1.4. Temporal Variability of Sound Levels

Initial analysis of the temporal variability of sound levels as a function of time of day and day of the week showed that the main temporal trend was associated with tidal cycles. Over a several week period, the currents often peaked at roughly the same time of day, which elevated (primarily) the lower frequency bands. In summer, there was also a small increase in the decade bands above 100 Hz during the day, likely associated with recreational vessel traffic. Figure 17 shows the daily rhythm plot for the synodic month starting 16 June 2019 as well as the median current speed in the same 10-minute intervals. The tidal cycle appears to elevate sound levels during the latter half of the day. The higher-frequency decade bands are elevated between approximately 08:00 and 20:00 (PST), which is likely related to a combination of the tidal cycle and recreational summer vessel traffic.

Longer term trends in sound levels are shown in the top half of Figure 18. These plots show the trends in sound level statistics computed over the synodic month periods in the entire frequency band and in the decade bands. The increase in sound levels for the synodic month starting in May is largely attributed to mooring noise from the mooring on AMAR 419. This synodic month was represented by acoustic data recorded entirely on AMAR 419. Although the same mooring design was used for all AMARs, the mooring for AMAR 419 produced higher levels of mooring noise than the other moorings. Mooring noise on AMAR 418, which recorded data prior to that of AMAR 419, and AMARs 424 and 429, which recorded data after AMAR 419, was much quieter. Sound levels for the synodic month starting in June were represented by data from AMARs 419, 424, and 429, so the levels were lower relative to those from the prior month. Mooring noise is discussed further in Section 3.1.5, where we show comparisons between sounds recorded simultaneously between two AMARs.

To reduce some of the effect of mooring noise, we recomputed the synodic month sound level statistics after filtering out time periods when current speeds were greater than 0.5 m/s (Figure 18 bottom). After applying this filtering, the higher-level statistics were more consistent with time, but there was little change in the lower-level statistics.

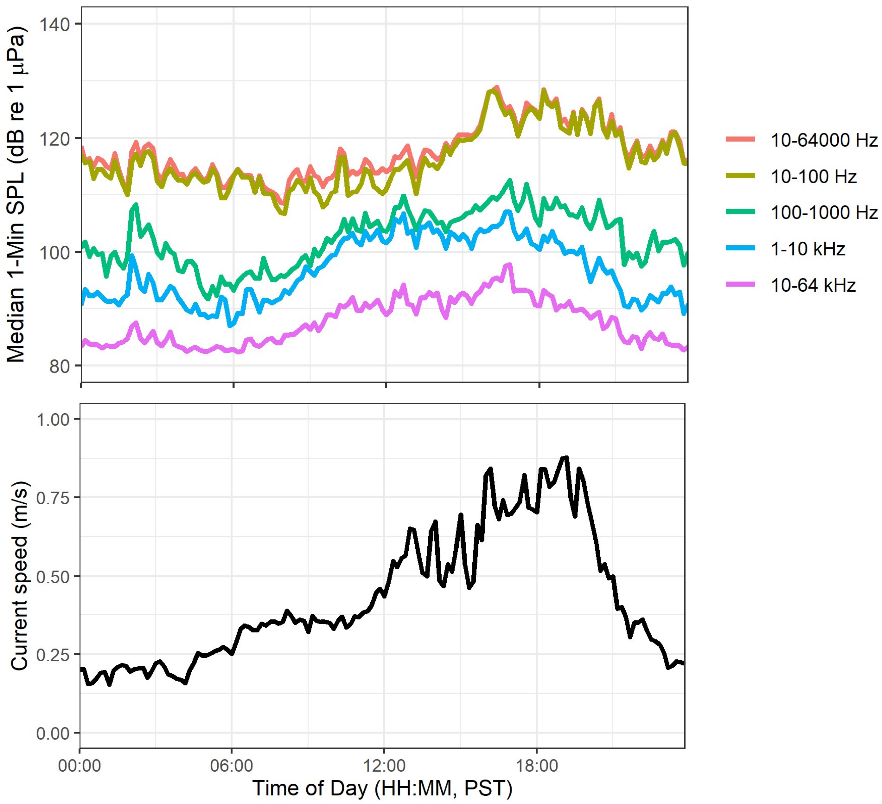
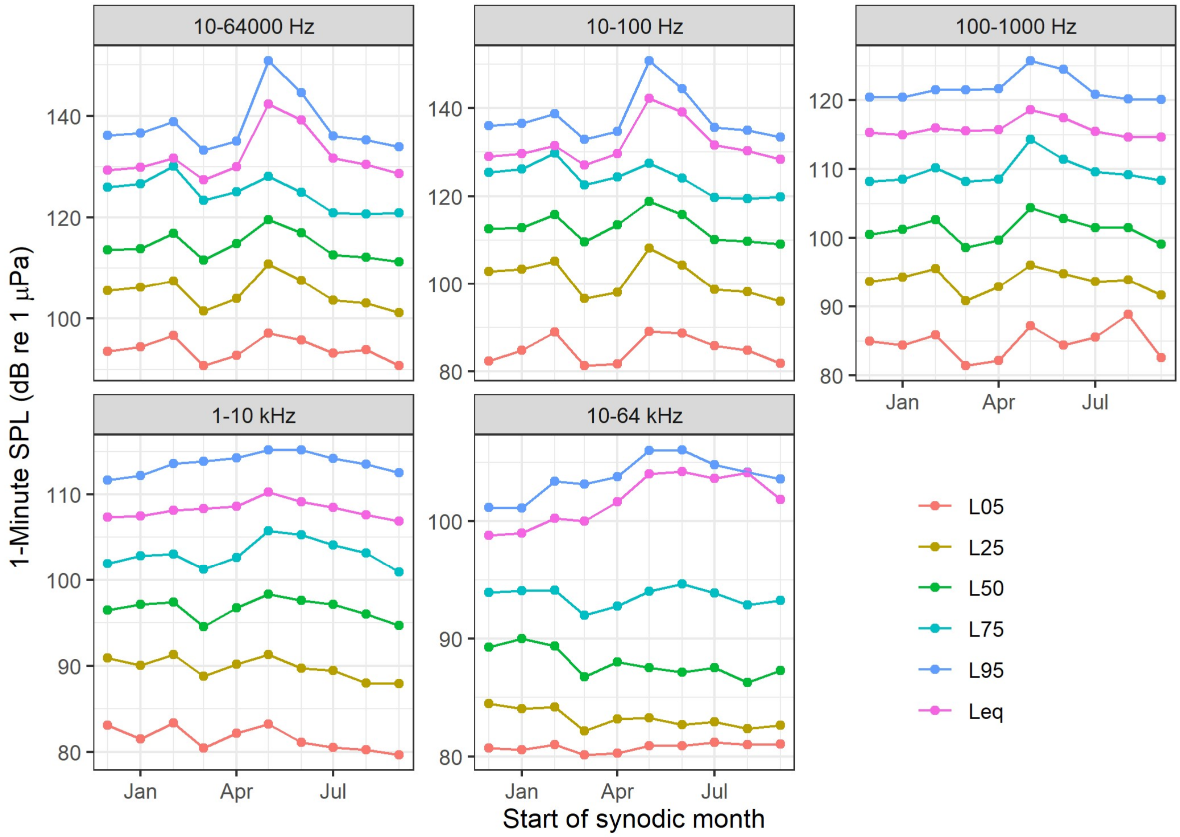


Figure 17. Sound levels (top) and current speed (bottom) as a function of time of day the synodic month starting 16 June 2019.



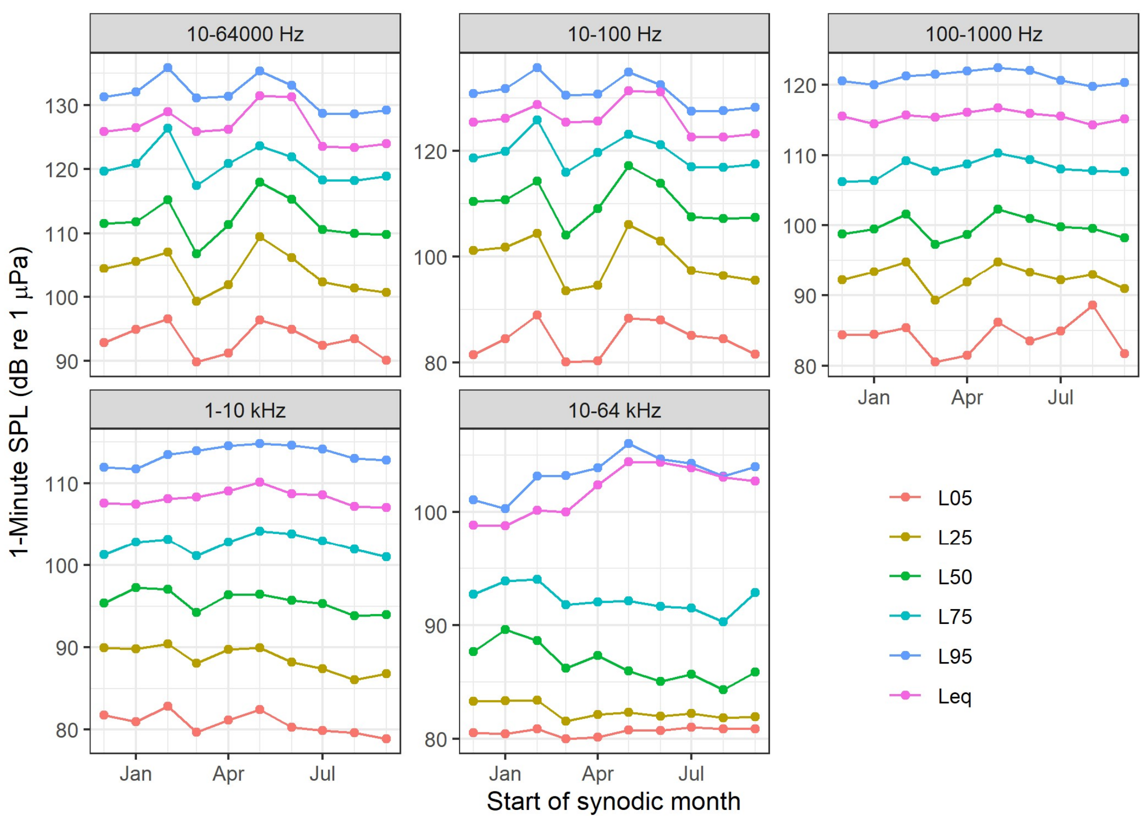


Figure 18. Synodic month sound level statistics as functions of time in each indicated frequency band (top) before and (bottom) after filtering out periods with current speeds greater than 0.5 m/s.

3.1.5. Comparison of Sound Levels Between Recorders

During each deployment, there were periods when both AMARs recorded simultaneously. For Deployments 1 and 2, the simultaneous recording periods were continuous and lasted for 15.7 and 9.3 days, respectively. For Deployment 3, the simultaneous recording period occurred between 07:00 and 08:00 (PST) every day, for a total equivalent duration of 8.7 days.

Although the AMAR pairs for each deployment were deployed using the same mooring design and within 120 m of each other, there were differences in the ambient noise levels for concurrent recording periods. Figures 19–21 show example waveforms and spectrograms for simultaneous 5-minute recordings from each deployment period. The time periods were selected such that AIS vessels were absent (none within 6 km) and current speeds were less than 0.5 m/s.

In Figure 19 (Deployment 1), low-frequency impulsive noise is visible in the spectrogram for AMAR 436 but not for AMAR 437. In Figure 20 (Deployment 2), there is low-frequency noise in both recordings, but it is more frequent for AMAR 419 than for AMAR 418. In Figure 21 (Deployment 3), there are higher levels of low-frequency noise for AMAR 424 than for AMAR 429.

The differences in sound levels occurred mainly in frequencies below 400 Hz and are largely attributed to mooring noise. Impulsive, low-frequency knocking sounds may have been caused by debris hitting the hydrophone or from current-induced mooring vibrations.

Figure 22 shows the decidecade band level distributions from both AMARs during the simultaneous recording period from Deployment 1. The data in Figure 22 have been filtered to exclude minutes where AIS-broadcasting vessels were within 6 km of the hydrophone or when current speeds were greater than 0.5 m/s to show the differences during quieter times. The differences were largest in the lowest frequency bands but were relatively small for frequencies above 400 Hz. During louder periods, when AIS-broadcasting vessels were nearby, the decidecade distributions were in much better agreement because the louder sounds from the vessels masked the mooring noise. Figure 23 shows the decidecade distributions when AIS-broadcasting vessels were within 6 km of the hydrophone (and current speeds were less than 0.5 m/s). During these times, the differences were mainly limited to frequencies less than 30 Hz.

Decidecade distributions for simultaneous recordings during Deployments 2 and 3 are shown in Appendix D.

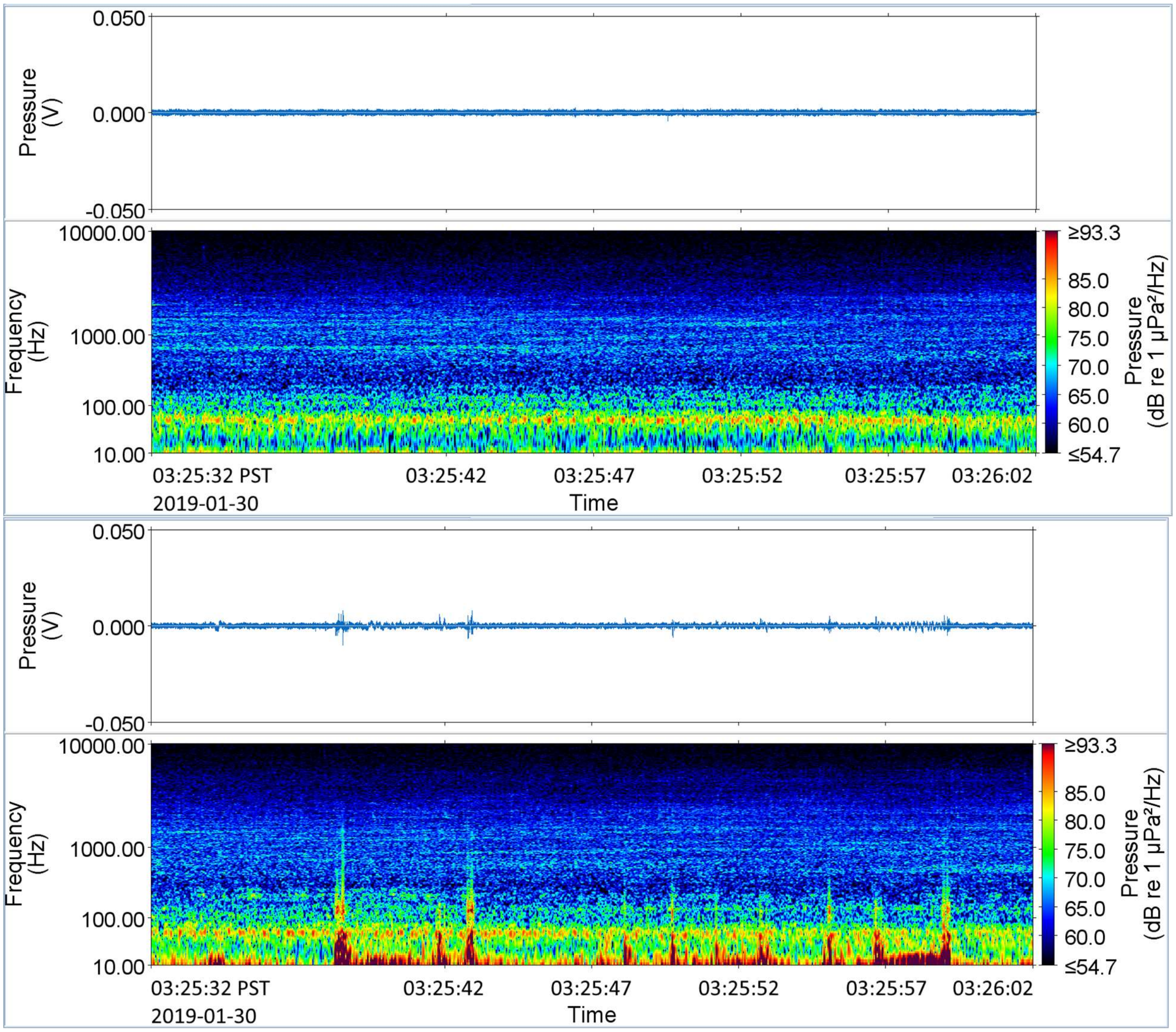


Figure 19. *Comparing sounds between recorders, Deployment 1*: Waveforms and spectrograms of acoustic pressure for two simultaneously recording AMARs over a 30-second period. Top panels are from AMAR 437, bottom panels are from AMAR 436.

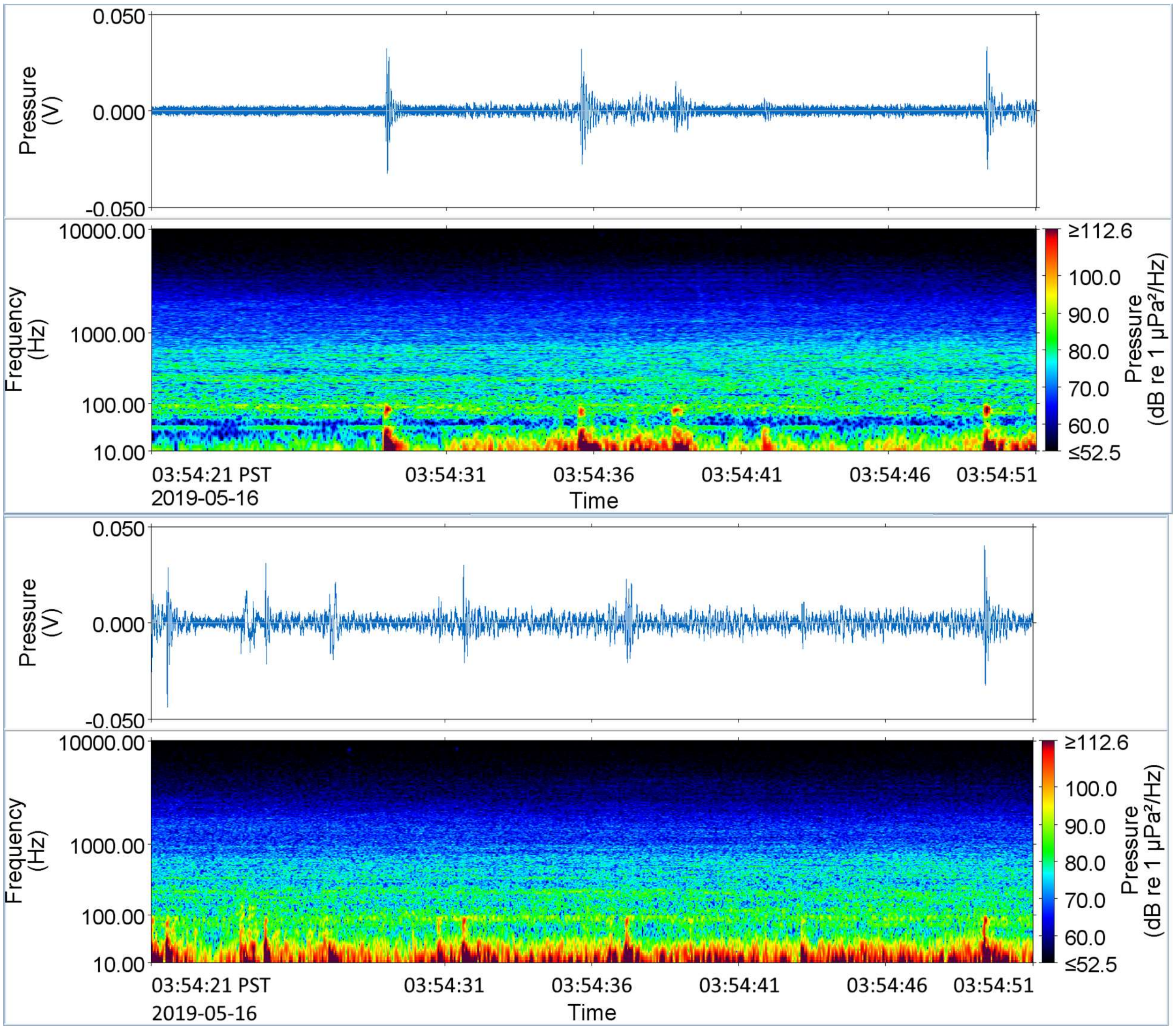


Figure 20. *Comparing sounds between recorders, Deployment 2:* Waveforms and spectrograms of acoustic pressure for two simultaneously recording AMARs over a 30-second period. Top panels are from AMAR 418, bottom panels are from AMAR 419.

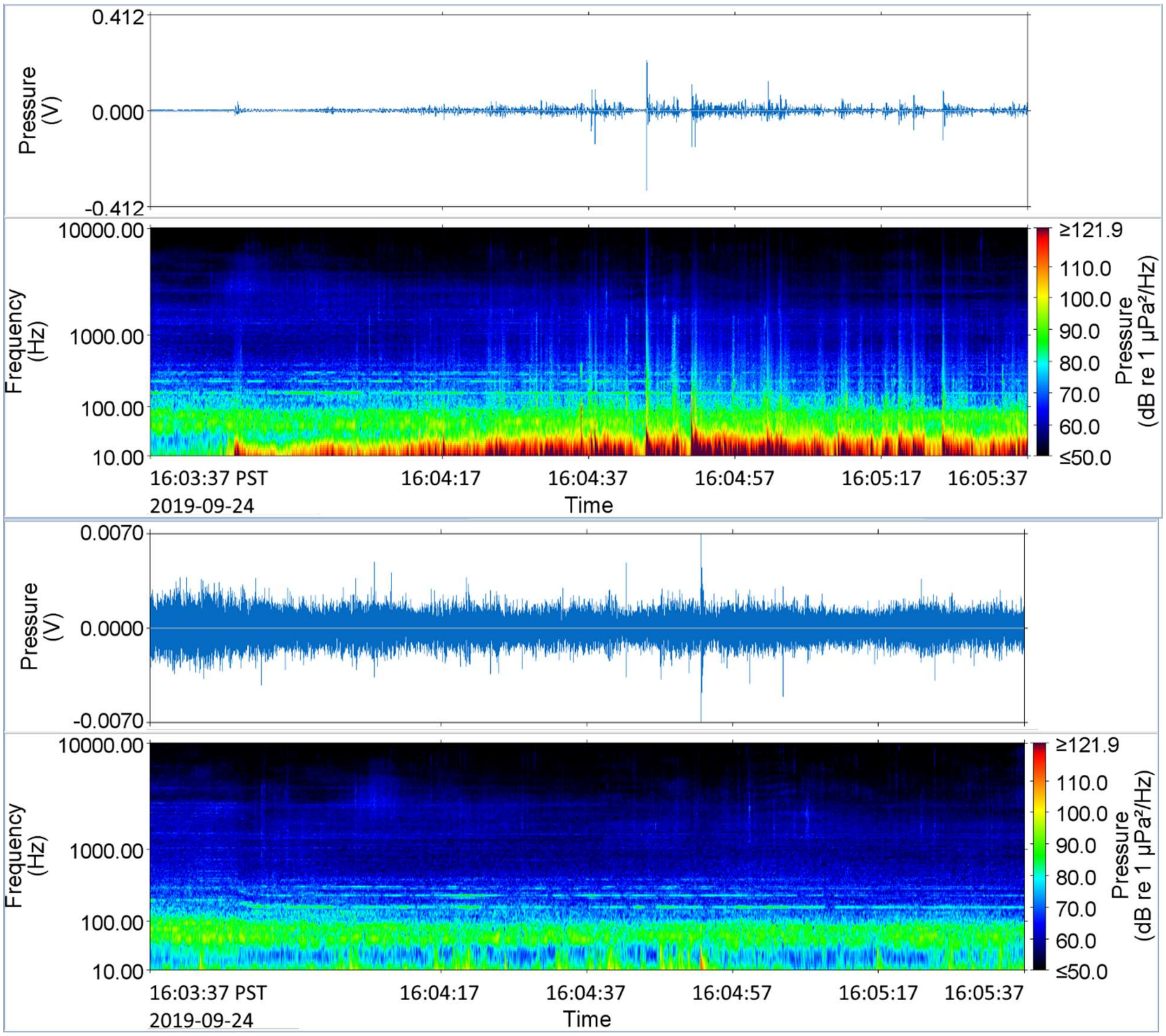


Figure 21. *Comparing sounds between recorders, Deployment 3:* Waveforms and spectrograms of acoustic pressure for two simultaneously recording AMARs over a 2-minute period. Top panels are from AMAR 424, bottom panels are from AMAR 429.

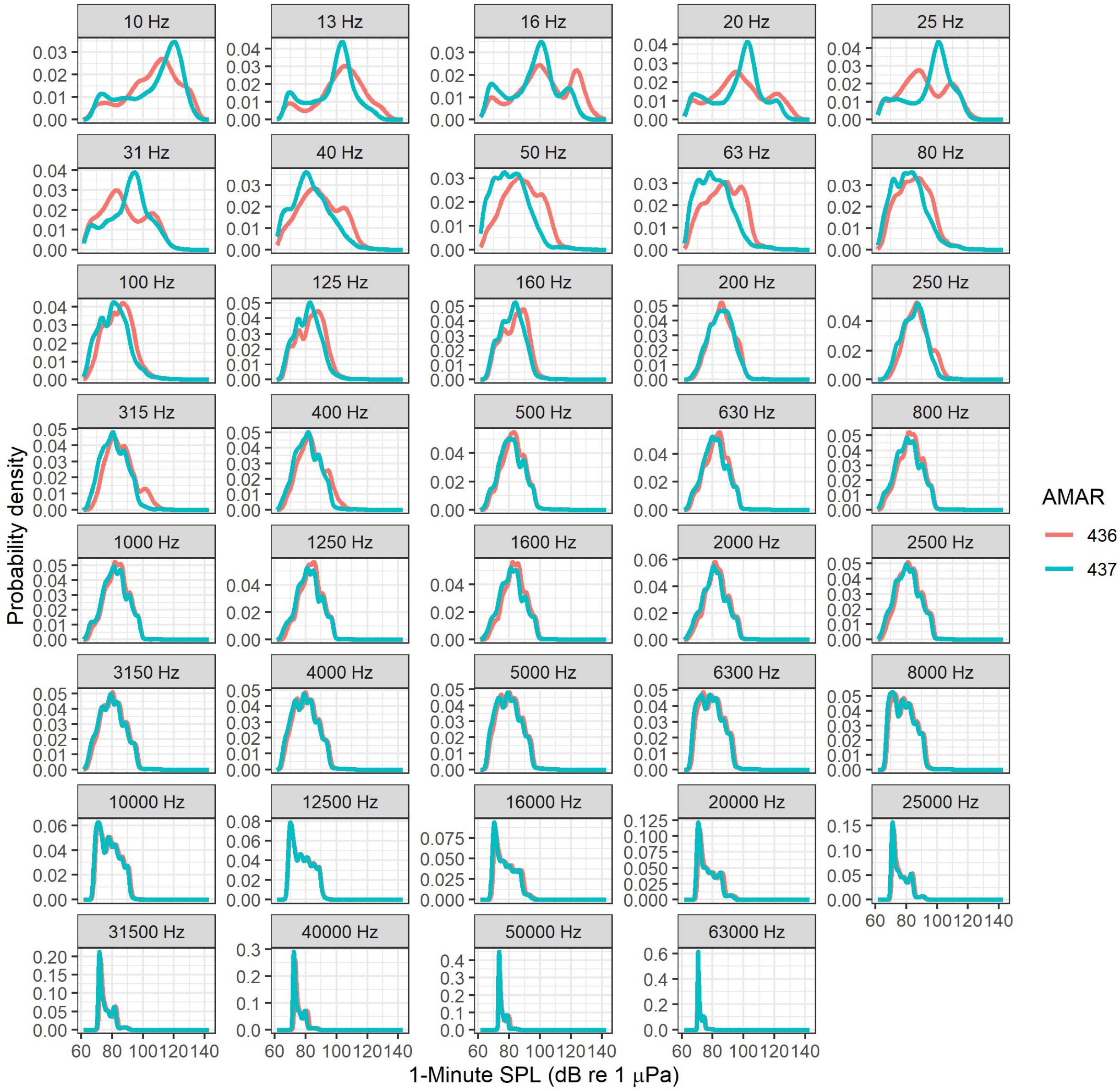


Figure 22. *Comparing sound level distributions during periods without vessels, Deployment 1:* Decidecade band sound level distributions, during AIS vessel absence, measured by simultaneously recording AMARs (10324 minutes). Data were pre-filtered to exclude minutes when AIS vessels were within 6 km of the hydrophones and/or when current speeds were greater than 0.5 m/s. Panel headings indicate the centre frequency of the decidecade band.

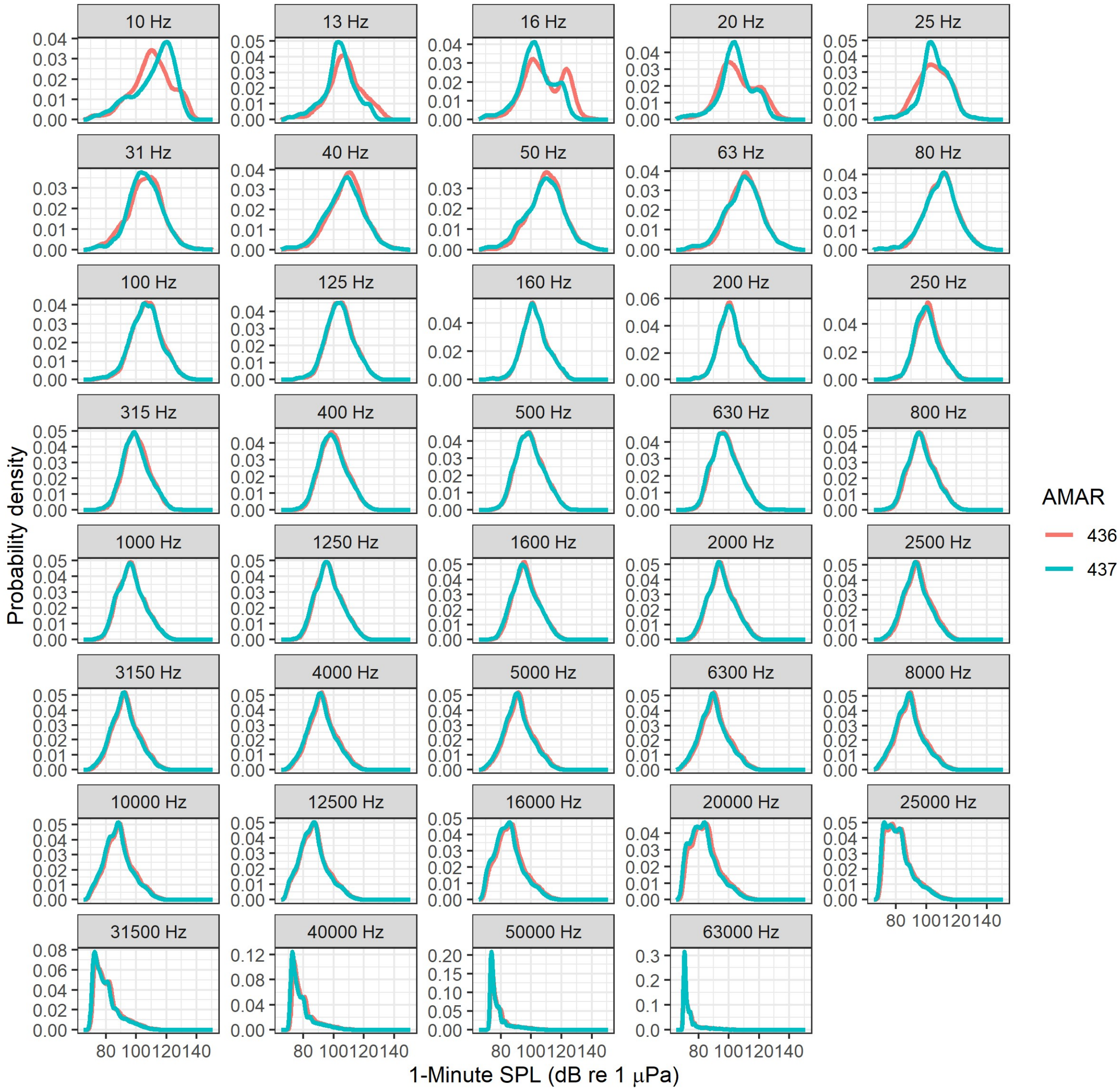


Figure 23. *Comparing sound level distributions during periods with vessels, Deployment 1:* Decidecade band sound level distributions when AIS-broadcasting vessels were within 6 km of the hydrophones, as measured by simultaneously recording AMARs (4003 minutes). Data were pre-filtered to exclude minutes when current speeds were greater than 0.5 m/s. Panel headings indicate the centre frequency of the decidecade band.

3.2. Marine Mammal Detection Results

A total of 8940 killer whale vocalizations and 1094 humpback whale vocalizations were reported by the automated detector at Boundary Pass for Deployments 1–3 (Year 1, 12 Dec 2018 to 15 Oct 2019). No Pacific white-sided dolphin vocalizations were detected at Boundary Pass during this period. Figure 24 shows the proportion of detections by species for this period. The hourly and daily detection counts of killer whale vocalizations and humpback whale vocalizations are illustrated in Figure 25 and Figure 26, respectively.

In total, killer whale vocalizations were detected on 74 days (24% of the recording period, Table 4). Most of these were in July (13 days). In total, humpback whale vocalizations were detected on 19 days (6% of the recording period, Table 4). Most of these were in July (7 days) or December (6 days). No Pacific white-sided dolphins were detected on Boundary Pass recordings during the reporting period.

Some spectrograms of killer whale vocalizations and humpback whale vocalizations are illustrated in Figure 27.

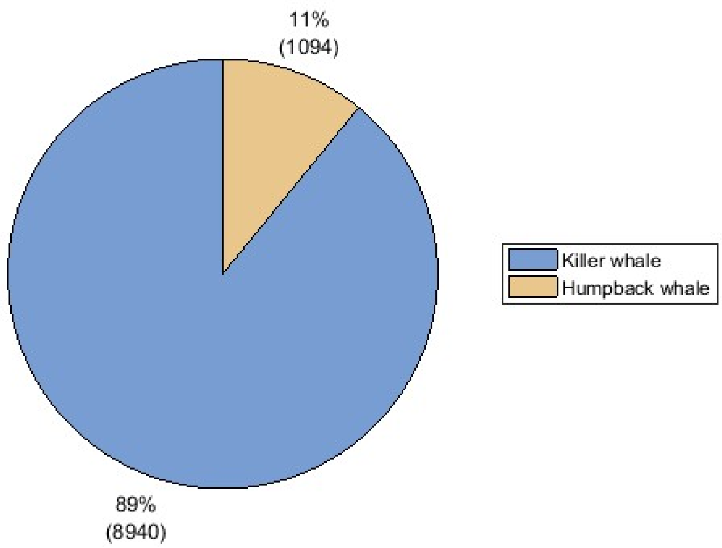


Figure 24. Proportion of detections by species for Year 1 (Deployments 1–3, 12 Dec 2018 to 15 Oct 2019).

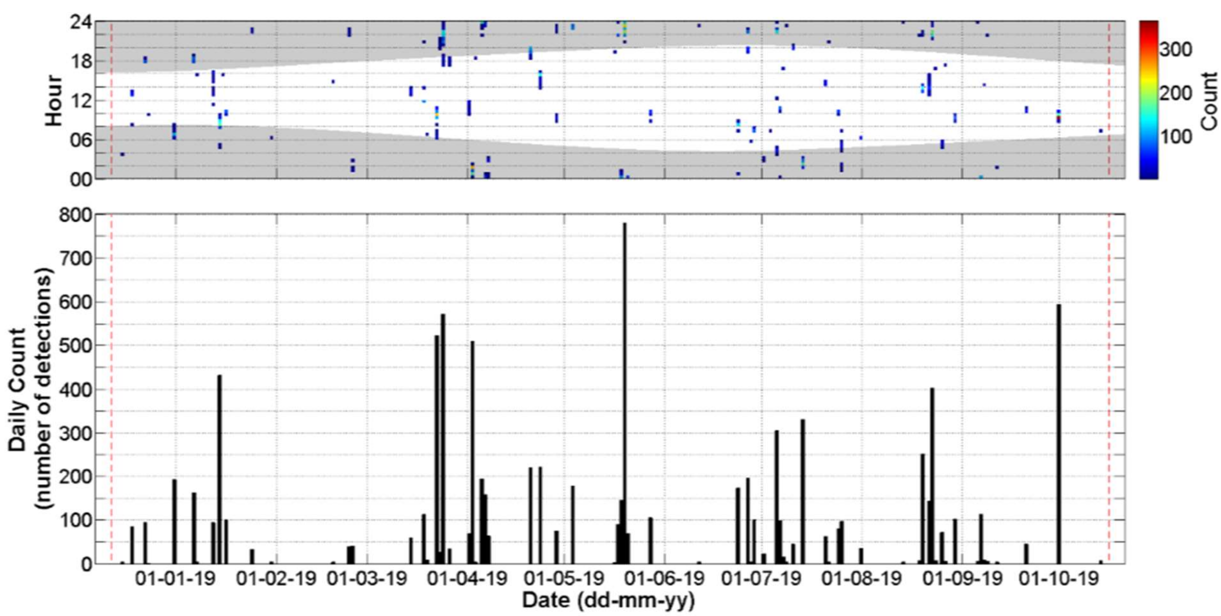


Figure 25. (Top) Hourly and (bottom) daily detection counts (PST) of killer whale vocalizations for Year 1 (Deployments 1–3 ,12 Dec 2018 to 15 Oct 2019). In the top panel, sunset to sunrise hours are shaded in grey.

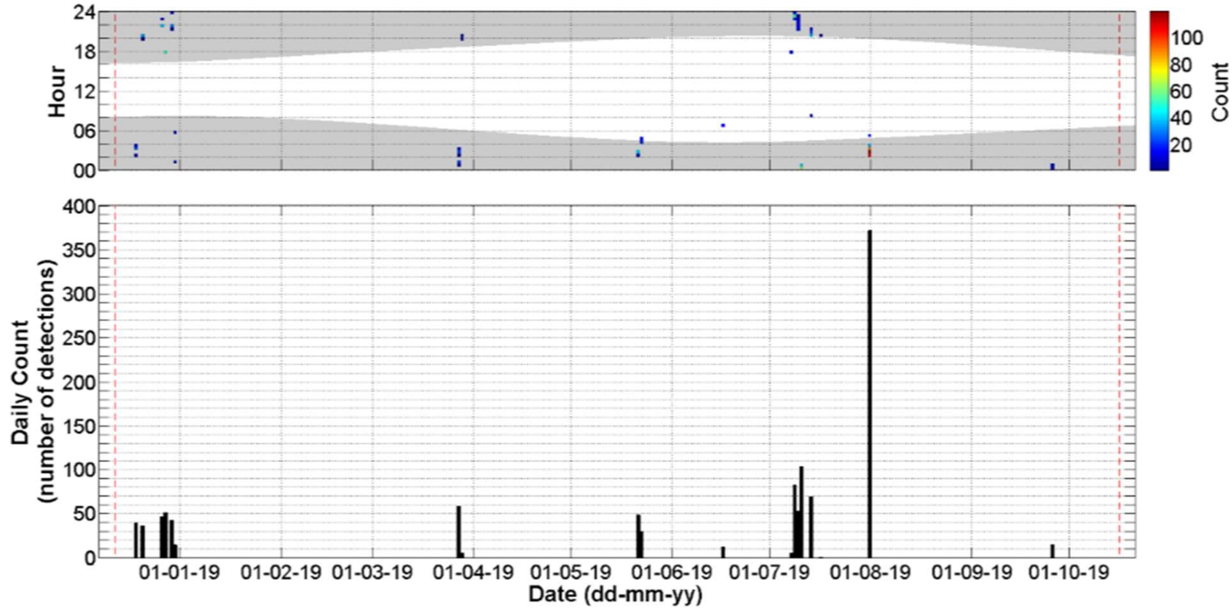


Figure 26. (Top) Hourly and (bottom) daily detection counts (PST) of humpback whale vocalizations for Year 1 (Deployments 1–3, 12 Dec 2018 to 15 Oct 2019). In the top panel, sunset to sunrise hours are shaded in grey.

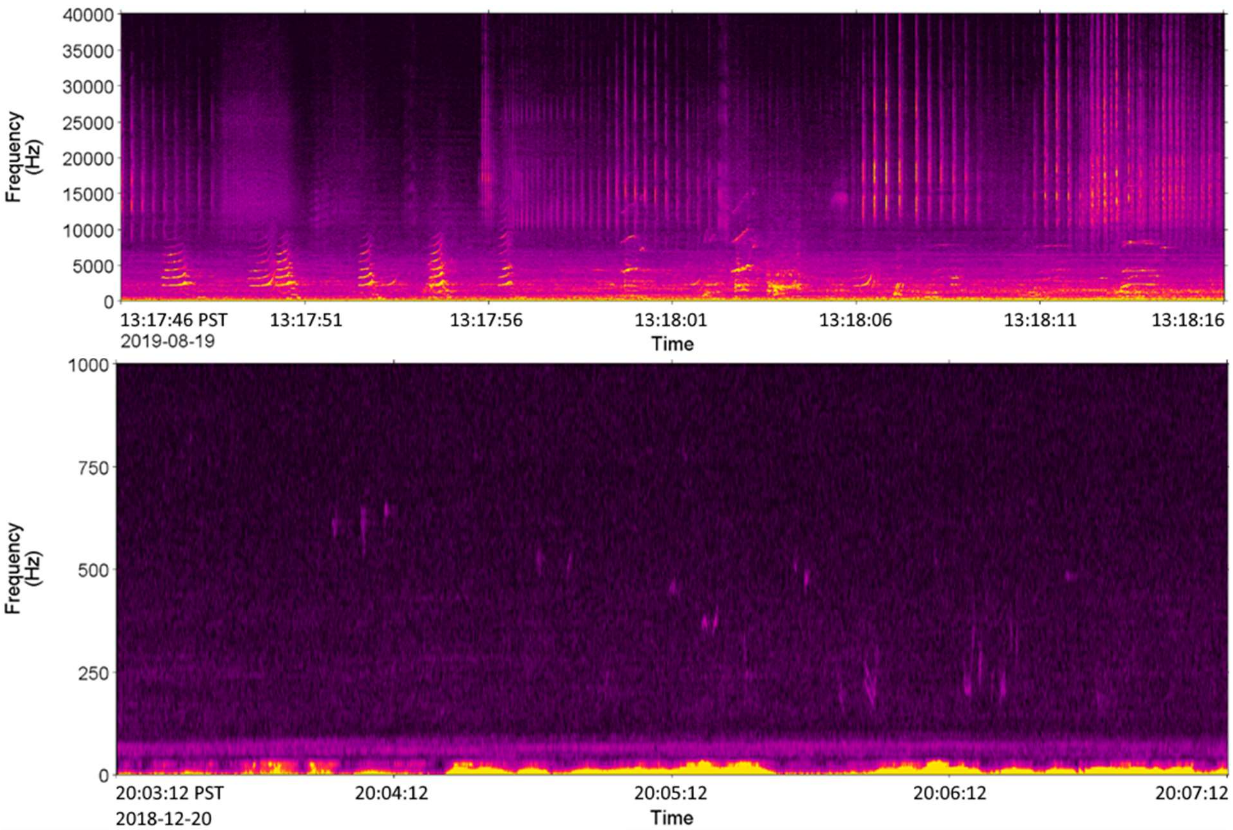


Figure 27. Spectrogram of vocalizations from (top) killer whales on 19 Aug 2019 and humpback whales on 20 Dec 2018. The top panel shows 30 seconds of data, and the bottom panel, 240 seconds.

Table 4. Number of marine mammal detections and days with detections by calendar month and species for Year 1 (Deployments 1–3).

Month	Humpback whale		Killer whale		Pacific white sided dolphin	
	Number of detections	Days with detections	Number of detections	Days with detections	Number of detections	Days with detections
Dec 2018	234	6/20	383	5/20*	0	0/20
Jan 2019	0	0/31	838	8/31	0	0/31
Feb 2019	0	0/28	88	3/28	0	0/28
Mar 2019	65	2/31	1342	7/31	0	0/31
Apr 2019	0	0/30	1522	9/30	0	0/30
May 2019	79	2/31	1374	7/31	0	0/31
Jun 2019	13	1/30	483	5/30	0	0/30
Jul 2019	688	7/31	1116	13/31	0	0/31
Aug 2019	0	0/31	1003	9/31	0	0/31
Sep 2019	15	1/30	783	7/30	0	0/30
Oct 2019	0	0/16	8	1/16†	0	0/16

* Total number of recording days was only 20 because the recordings began on 12 Dec 2018 (see Table 1).
† Total number of recording days recorded was only 16 because the recordings stopped on 15 Oct 2019 (see Table 1).

3.3. Vessel Source Level Measurement Summary

A total of 6140 vessel source level measurements were made using JASCO's ShipSound application during the study period (Deployments 1–3). Of these, approximately 68% passed the manual quality control checks. Figure 28 shows the number of accepted measurements by vessel category for each month. The number of measurements are lower for the first and last months (Dec 2018 and Oct 2019) because data were acquired for approximately half of those calendar months. Appendix E contains tables of the number of accepted measurements and the acceptance rates corresponding to the data shown in Figure 28. Table 5 lists radiated noise levels (RNL) statistics by vessel category for all accepted measurements during the study period (Deployments 1–3). Monopole source levels (MSL) for vessel categories with more than 50 accepted measurements during the study period (Deployments 1–3) are shown in Figure 29.

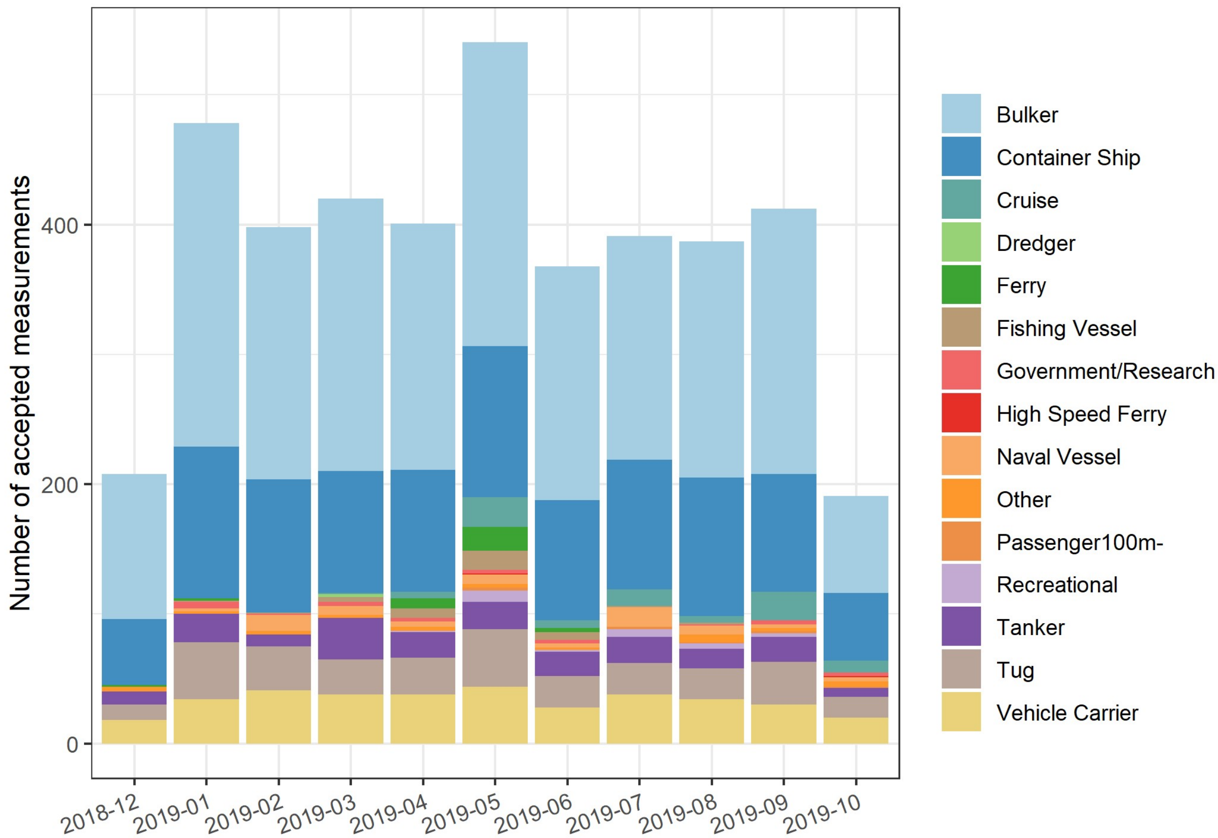


Figure 28. Number of vessel source level measurements, by vessel category, that passed the manual quality control checks for each calendar month.

Table 5. Summary of broadband radiated noise levels (RNL) by vessel category.

Vessel Class	Max RNL (dB re 1 µPa m)	Average RNL (dB re 1 µPa m)	Min RNL (dB re 1 µPa m)	Number of Transits
Bulker <200	202.9	188.4	175.0	938
Bulker >=200	206.2	189.0	174.9	1064
Container Ship <200	185.8	185.8	185.8	1
Container Ship >=200	209.0	192.2	179.0	1017
Dredger	186.1	186.0	185.8	2
Ferry >=50	195.3	186.1	174.4	32
Fishing Vessel	191.9	181.3	174.8	36
Government/Research	191.6	177.7	167.2	25
High Speed Ferry	178.8	178.7	178.7	2
Naval Vessel	185.4	167.7	158.5	63
Other	194.5	184.1	168.0	31
Passenger >=100	196.1	184.2	172.3	84
Passenger <100	185.6	177.1	167.4	8
Recreational	194.2	177.9	161.1	24
Tanker	198.2	187.3	177.4	194
Tug <50	202.0	181.7	168.5	284
Tug >=50	195.6	187.3	181.0	26
Vehicle Carrier	205.0	189.5	177.9	363

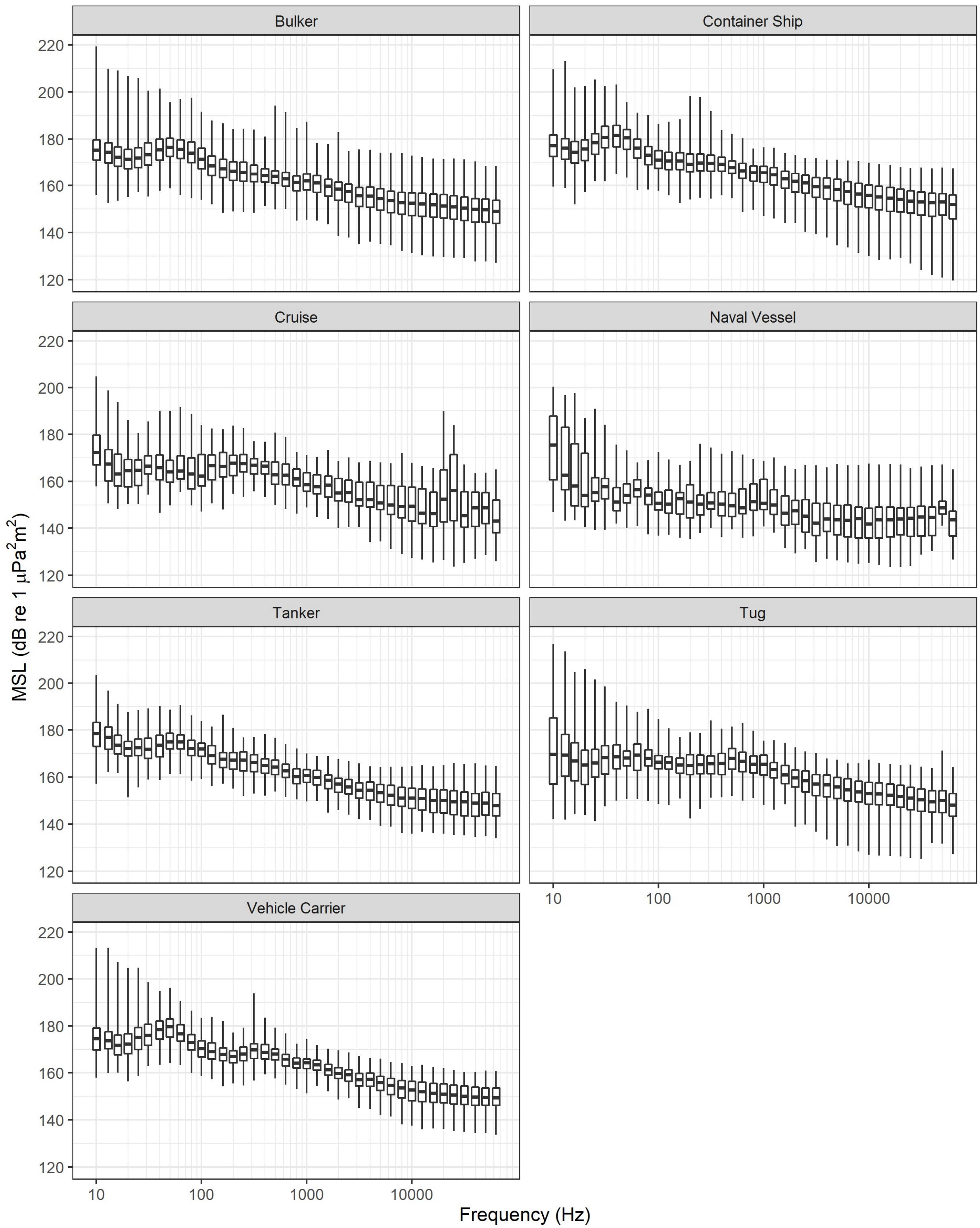


Figure 29. Box-and-whisker plots of monopole source levels (MSL) for vessel categories with more than 50 accepted measurements during the study period (Deployments 1–3).

4. Discussion and Conclusion

Ambient noise in Boundary Pass was found to be affected by current-induced water flow and mooring noise, wind speed, and vessel traffic. Of these factors, water currents and vessel traffic produced the largest effects.

The fast currents in Boundary Pass (up to ~2 m/s or ~4 knots) caused elevated sound levels primarily in the 10-100 Hz band when near-seafloor current speeds exceeded 0.5 m/s. There is some uncertainty, however, if the near-seafloor current speeds measured at the ADCP deployment location are representative of the near-seafloor currents at the AMARs. The ADCP was deployed approximately 1.5 km from the AMARs (to prevent their pings from contaminating the acoustic data), and the water depth was half as deep at the ADCP (~100 m depth) than at the AMAR locations (~200 m depth). This uncertainty will likely be resolved with the deployment of the cabled ULS because an ADCP will be deployed on the ULS frame.

The AMARs were all deployed using the same mooring design, yet some of the moorings produced more mooring noise than others. For example, the mooring for AMAR 419 produced sound throughout its recording period (8 May to 3 Jul, 2019) that affected both the high and low sound level statistics (see Figure 18 top). The high levels appeared to be related to high current speeds (see Figure 18 bottom). The effect on the lower levels was likely due to persistent low-speed currents and knocking of the hydrophone or movement of the mooring (see Figure 20).

Decidecade sound levels measured by two AMARs at the same time showed differences in the lower frequency bands. During quiet periods (without AIS vessel presence), differences were observed for bands centred at or below 400 Hz (e.g., Figure 22). During louder periods (e.g., with AIS vessel presence), the differences were observed in fewer frequency bands, at or below ~30 Hz (e.g., Figure 23). These differences may be caused by differences in low-frequency mooring noise. The cabled ULS that will replace the autonomous recorders in Boundary Pass will have a rigid mooring and will remain installed for multiple years, so it should provide a more consistent measurement of low-frequency ambient sound levels.

Vessel traffic, assessed using AIS records, increased ambient sound levels substantially. Median broadband sound levels increased by ~14 dB when AIS vessels were within 6 km of the hydrophone. The increases were largest in the 10-100 Hz, 100-1000 Hz, and 1-10 kHz bands. The higher frequency 10-64 kHz band also increased substantially for the L_5 percentile. This may have been caused by hull-mounted high-frequency sonars elevating ambient sound levels during relatively brief periods as the vessels transited over the AMARs.

Over 10000 manually-validated marine mammal detections were found in the acoustic data for the ~10 month study period. Most (89%) of these were from killer whales, and the detections occurred throughout all months of the study period (see Figure 25). The remaining detections were from humpback whales, which were found in all seasons but not all months. For both species, the detections occurred in relatively short intervals.

Over 6000 vessel source level measurements were analyzed with JASCO's ShipSound application. A large fraction of these measurements were of bulker and container ships (see Figure 28). The hydrophone location was suitable for processing source level measurements for vessels travelling in both the incoming and outgoing international shipping lane and provided a higher rate of vessel source level measurements than the Strait of Georgia ULS.

Once the cabled ULS is installed, the acoustic data will be compared to that from the autonomous AMARs reported here. This will provide information about the differences observed in low-frequency sound levels between hydrophones, mooring susceptibility to current-induced flow noise, and differences in near-seafloor current speeds at different depths. We expect the rigid mooring design of the ULS to produce less mooring noise than the designs used for the autonomous recorders. This may allow detection of quieter marine mammal calls and provide a consistent measurement platform to quantify long-term trends in ambient noise levels in Boundary Pass.

Acknowledgements

We thank Mitch Herron and the crew of the *Richardson Point*, and Greg Bellavance and the crew of the *Moving Experience* for their assistance with deploying and retrieving the underwater monitoring equipment. We also thank Andy Clark and the crew of the Crown Royal for battling the Boundary Pass currents with their ROV to retrieve one of our ADCPs. We thank David Osborne for allowing us to install our shore-based AIS logger at his home on Saturna Island. JASCO's field teams included David Hannay, Héloïse Frouin-Mouy, Jennifer Wladichuk, and Graham Warner.

Glossary

1/3-octave
One third of an octave. Note: A one-third octave is approximately equal to one decidecade (1/3 oct ≈ 1.003 ddec; ISO 2017).

1/3-octave-band
Frequency band whose bandwidth is one one-third octave. Note: The bandwidth of a one-third octave-band increases with increasing centre frequency.

absorption
The reduction of acoustic pressure amplitude due to acoustic particle motion energy converting to heat in the propagation medium.

ambient noise
All-encompassing sound at a given place, usually a composite of sound from many sources near and far (ANSI S1.1-1994 R2004), e.g., shipping vessels, seismic activity, precipitation, sea ice movement, wave action, and biological activity.

attenuation
The gradual loss of acoustic energy from absorption and scattering as sound propagates through a medium.

background noise
Total of all sources of interference in a system used for the production, detection, measurement, or recording of a signal, independent of the presence of the signal (ANSI S1.1-1994 R2004). Ambient noise detected, measured, or recorded with a signal is part of the background noise.

bandwidth
The range of frequencies over which a sound occurs. Broadband refers to a source that produces sound over a broad range of frequencies (e.g., seismic airguns, vessels) whereas narrowband sources produce sounds over a narrow frequency range (e.g., sonar) (ANSI/ASA S1.13-2005 R2010).

box-and-whisker plot
A plot that illustrates the centre, spread, and overall range of data from a visual 5-number summary. The ends of the box are the upper and lower quartiles (25th and 75th percentiles). The horizontal line inside the box is the median (50th percentile). The whiskers extend outside the box to the highest and lowest observations.

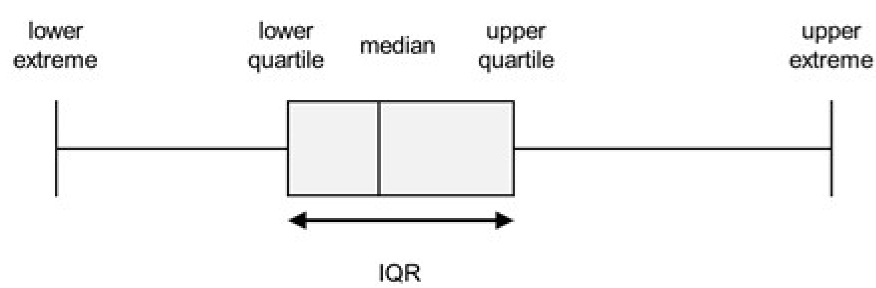


Figure 30. Diagram showing how quantiles are displayed on a box-and-whisker plot. IQR = interquartile range (i.e., the range between the 25th and 75th percentile).

broadband sound level
The total sound pressure level measured over a specified frequency range. If the frequency range is unspecified, it refers to the entire measured frequency range.

cetacean
Any animal in the order Cetacea. These are aquatic, mostly marine mammals and include whales, dolphins, and porpoises.

decade
Logarithmic frequency interval whose upper bound is ten times larger than its lower bound (ISO 2006).

decidecade
One tenth of a decade (ISO 2017). Note: An alternative name for decidecade (symbol ddec) is “one-tenth decade”. A decidecade is approximately equal to one third of an octave (1 ddec ≈ 0.3322 oct) and for this reason is sometimes referred to as a “one-third octave”.

decidecade band
Frequency band whose bandwidth is one decidecade. Note: The bandwidth of a decidecade band increases with increasing centre frequency.

decibel (dB)
One-tenth of a bel. Unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power (ANSI S1.1-1994 R2004).

frequency
The rate of oscillation of a periodic function measured in cycles-per-unit-time. The reciprocal of the period. Unit: hertz (Hz). Symbol: f. 1 Hz is equal to 1 cycle per second.

Global Positioning System (GPS)
A satellite based navigation system providing accurate worldwide location and time information.

hertz (Hz)
A unit of frequency defined as one cycle per second.

hydrophone
An underwater sound pressure transducer. A passive electronic device for recording or listening to underwater sound.

impulsive sound
Sound that is typically brief and intermittent with rapid (within a few seconds) rise time and decay back to ambient levels (NOAA 2013, ANSI S12.7-1986 R2006). For example, seismic airguns and impact pile driving.

mean-square sound pressure spectral density
Distribution as a function of frequency of the mean-square sound pressure per unit bandwidth (usually 1 Hz) of a sound having a continuous spectrum (ANSI S1.1-1994 R2004). Unit: $\mu Pa^2/Hz$.

median
The 50th percentile of a statistical distribution.

octave
The interval between a sound and another sound with double or half the frequency. For example, one octave above 200 Hz is 400 Hz, and one octave below 200 Hz is 100 Hz.

percentile level, exceedance
The sound level exceeded *n*% of the time during a measurement.

power spectrum density
Generic term, formally defined as power in W/Hz, but sometimes loosely used to refer to the spectral density of other parameters such as square pressure or time-integrated square pressure.

pressure, acoustic
The deviation from the ambient hydrostatic pressure caused by a sound wave. Also called overpressure. Unit: pascal (Pa). Symbol: *p*.

pressure, hydrostatic
The pressure at any given depth in a static liquid that is the result of the weight of the liquid acting on a unit area at that depth, plus any pressure acting on the surface of the liquid. Unit: pascal (Pa).

rms
root-mean-square.

sound
A time-varying pressure disturbance generated by mechanical vibration waves travelling through a fluid medium such as air or water.

sound pressure level (SPL)
The decibel ratio of the time-mean-square sound pressure, in a stated frequency band, to the square of the reference sound pressure (ANSI S1.1-1994 R2004).

For sound in water, the reference sound pressure is one micropascal (p_0 = 1 μPa) and the unit for SPL is dB re 1 μPa^2:

$$L_p = 10\log_{10}(p^2/p_0^2) = 20\log_{10}(p/p_0)$$

Unless otherwise stated, SPL refers to the root-mean-square (rms) pressure level. See also 90% sound pressure level and fast-average sound pressure level. Non-rectangular time window functions may be applied during calculation of the rms value, in which case the SPL unit should identify the window type.

sound speed profile
The speed of sound in the water column as a function of depth below the water surface.

source level (SL)
The sound level measured in the far-field and scaled back to a standard reference distance of 1 metre from the acoustic centre of the source. Unit: dB re 1 μPa^2·m^2 (pressure level) or dB re 1 μPa^2·s·m (exposure level).

spectral density level
The decibel level (10·log$_{10}$) of the spectral density of a given parameter such as SPL or SEL, for which the units are dB re 1 μPa^2/Hz and dB re 1 μPa^2·s/Hz, respectively.

spectrogram
A visual representation of acoustic amplitude compared with time and frequency.

spectrum
An acoustic signal represented in terms of its power, energy, mean-square sound pressure, or sound exposure distribution with frequency.

synodic month
The time period between consecutive lunar phases. The long-term average synodic lunar month period is 29 days, 12 hours, and 44 minutes.

transmission loss (TL)
The decibel reduction in sound level between two stated points that results from sound spreading away from an acoustic source subject to the influence of the surrounding environment. Also referred to as propagation loss.

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Appendix A. Example Ambient Noise Report for 1 Month

A.1. Introduction

JASCO Applied Sciences was contracted to the Vancouver Fraser Port Authority (VFPA) to analyze underwater sound in Boundary Pass as part of VFPA's Enhancing Cetacean Habitat and Observations (ECHO) program. Acoustic data were collected using JASCO's Autonomous Multichannel Acoustic Recorders (AMARs) starting 12 Dec 2018. This report contains analysis of data collected from the beginning of the recording period until 16 Jun 2019[2]. The acoustic data were processed to compute ambient noise statistics.

A.2. Report Schedule

The analysis was conducted over synodic lunar month periods (29 days, 12 hours, and 44 minutes), following the schedule used for the Strait of Georgia Underwater Listening Station. The table below lists the report schedule for the Boundary Pass data from 20 Dec 2018 to 16 Jun 2019. Unless otherwise noted, dates are for the year 2019.

Month start	Month end	Weeks reported
Thurs 20 Dec 2018, 22:33	Sat 19 Jan 2019, 11:17	Sun 16 Dec to Sun 23 Dec, 2018 Sun 23 Dec to Sun 30 Dec, 2018 Sun 30 Dec 2018 to Sun 6 Jan, 2019 Sun 6 Jan to Sun 13 Jan Sun Jan 13 to Sun 20 Jan
Sat 19 Jan, 11:17	Mon 18 Feb, 00:01	Sun 20 Jan to Sun 27 Jan Sun 27 Jan to Sun 3 Feb Sun 3 Feb to Sun 10 Feb Sun 10 Feb to Sun 17 Feb
Mon 18 Feb, 00:01	Tues 19 Mar, 13:45	Sun 17 Feb to Sun 24 Feb Sun 24 Feb to Sun 3 Mar Sun 3 Mar to Sun 10 Mar Sun 10 Mar to Sun 17 Mar
Tues 19 Mar, 13:34	Thurs 18 Apr, 02:29	Sun 17 Mar to Sun 24 Mar Sun 24 Mar to Sun 31 Mar Sun 31 Mar to Sun 7 Apr Sun 7 Apr to Sun 14 Apr Sun 14 Apr to Sun 21 Apr
Thurs 18 Apr, 02:29	Fri 17 May, 15:13	Sun 21 Apr to Sun 28 Apr Sun 28 Apr to Sun 5 May Sun 5 May to Sun 12 May Sun 12 May to Sun 19 May
Fri 17 May, 15:13	Sun 16 Jun, 03:57	Sun 19 May to Sun 26 May Sun 26 May to Sun 2 June Sun 2 Jun to Sun 9 Jun Sun 9 Jun to Sat 16 Jun

[2] This report has been truncated for this appendix to only show one synodic month of results.

A.3. Ambient Noise Data Processing Methods

Location Name: **Boundary Pass**

Analysis Period: **20 Dec 2018, 22:23 PST to 16 Jun 2019, 03:57 PDT**

Table 6. AMAR recorder locations and periods used for analysis. AMAR 437 and 418 data were used during time periods when two AMARs recorded simultaneously, because they appeared less susceptible to flow noise.

AMAR SN	Latitude (N)	Longitude (W)	Water Depth (m)	Start Date/Time	End Date/Time
437	48° 45.60665'	123° 3.86085'	197	2018-12-12 22:32	2019-02-07 16:42
436	48° 45.63044'	123° 3.79622'	199	2019-01-23 00:00	2019-03-20 18:21
418	48° 45.63369'	123° 3.77304'	197	2019-03-21 14:24	2019-05-17 07:31
419	48° 45.67526'	123° 3.74762'	196	2019-05-08 00:00	2019-07-03 18:03

This report summarizes ambient underwater noise measurements made in Boundary Pass during the analysis period. The results are presented in seven formats:

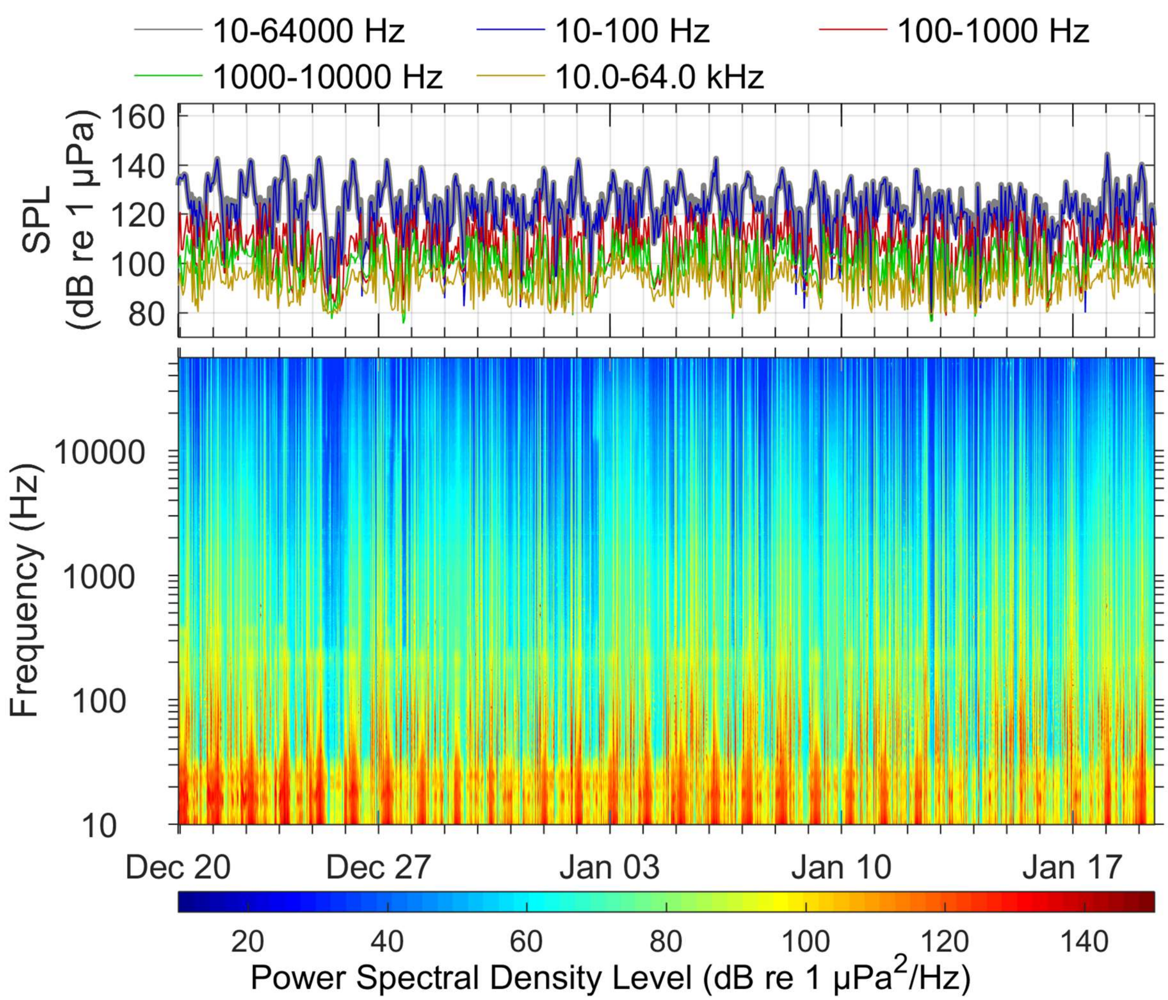
1. Combined plot of ambient sound pressure level (SPL) versus time and spectrogram: The broadband and decade band results represent SPL in 1-hour intervals over the analysis period. The results are presented in five frequency bands: 10–64000 Hz (broadband), 10–100 Hz, 100–1000 Hz, 1000–10000 Hz, and 10000–64000 Hz.
2. 1/3-octave-band and spectral level statistics: The spectral results are computed in 1-minute periods as averages of 1-second Hanning-windowed spectra with 50% overlap. The 1-minute averages are displayed at 5th, 25th, 50th, 75th, and 95th percentile levels, referred to as L_5, L_{25}, L_{50}, L_{75}, and L_{95}. By ANSI standard, L_5 is the sound level exceeded just 5% of the time and is therefore larger than L_{95}. The L_{50} is commonly referred to as the median. The frequency range displayed spans the acoustic bandwidth of the recording. The 1/3-octave levels are calculated similarly to the spectral levels, except the 1-minute spectra are first integrated within the 1/3-octave-bands with centre frequencies between 10 Hz and 50 kHz, which are then displayed at 5th, 25th, 50th, 75th, and 95th percentile levels. The mean band and spectral levels are also shown.
3. One-third-octave-band levels: A tabular presentation of the 1/3-octave-band and broadband results.
4. Daily rhythm plot: The data from the analysis period are examined in 10-minute steps throughout one day (i.e., from 0:00–0:10, 0:10–0:20, …, 23:50–24:00). The ten 1-minute bins in each 10-minute step are grouped with the same ten one-minute bins each day for all days of the month. This group of one-minute samples is then analyzed and its median value calculated. For example, in a 29-day month, the daily L_{50} for 12:00–12:10 is the median of the ten 1-minute samples each day for all 29 days (therefore from 290 one-minute samples). Plotting the daily cadences can reveal patterns associated with human activity such as ferries or other regularly scheduled vessel passages.
5. Weekly rhythm plot: Similar to the daily rhythm plot, the data are examined in 30-minute steps over a week. The 30 one-minute samples in each step are combined over multiple weeks, so over 4 weeks there are 120 samples. The samples are analyzed for median values. Plotting the weekly cadences can reveal patterns associated with human activity that vary on a weekly schedule, such as work week versus weekend differences.
6. SPL box plot: A summary of the broadband and decade-band statistics of SPL (1 minute) over the synodical month analysis period. A table of values accompanies each plot.
7. Weekly band level plots: Similar to the monthly ambient SPL versus time, the broadband and decade-band results represent SPL in 1-hour intervals over a calendar week, according to the methods specified for underwater ambient noise measurements by the ECHO program guidelines.

Wind and near-seafloor current speeds are also plotted following the acoustic data in each monthly section of the report. Hourly wind speeds were obtained from the Environment Canada station "Saturna Island CS". During time periods when wind speeds from the Saturna station were unavailable, data from the Environment Canada station "Kelp Reefs" was used instead. Near-seafloor current speeds were obtained from Acoustic Doppler Current Profiler (ADCP) measurements and were supplemented with the WebTide Tidal Prediction Model (v0.7.1) (Foreman et al. 2000, Institute of Ocean Sciences 2015) when ADCP measurements were unavailable (i.e., prior to 21 Mar 2019).

A.4. Results: 20 Dec 2018 to 19 Jan 2019

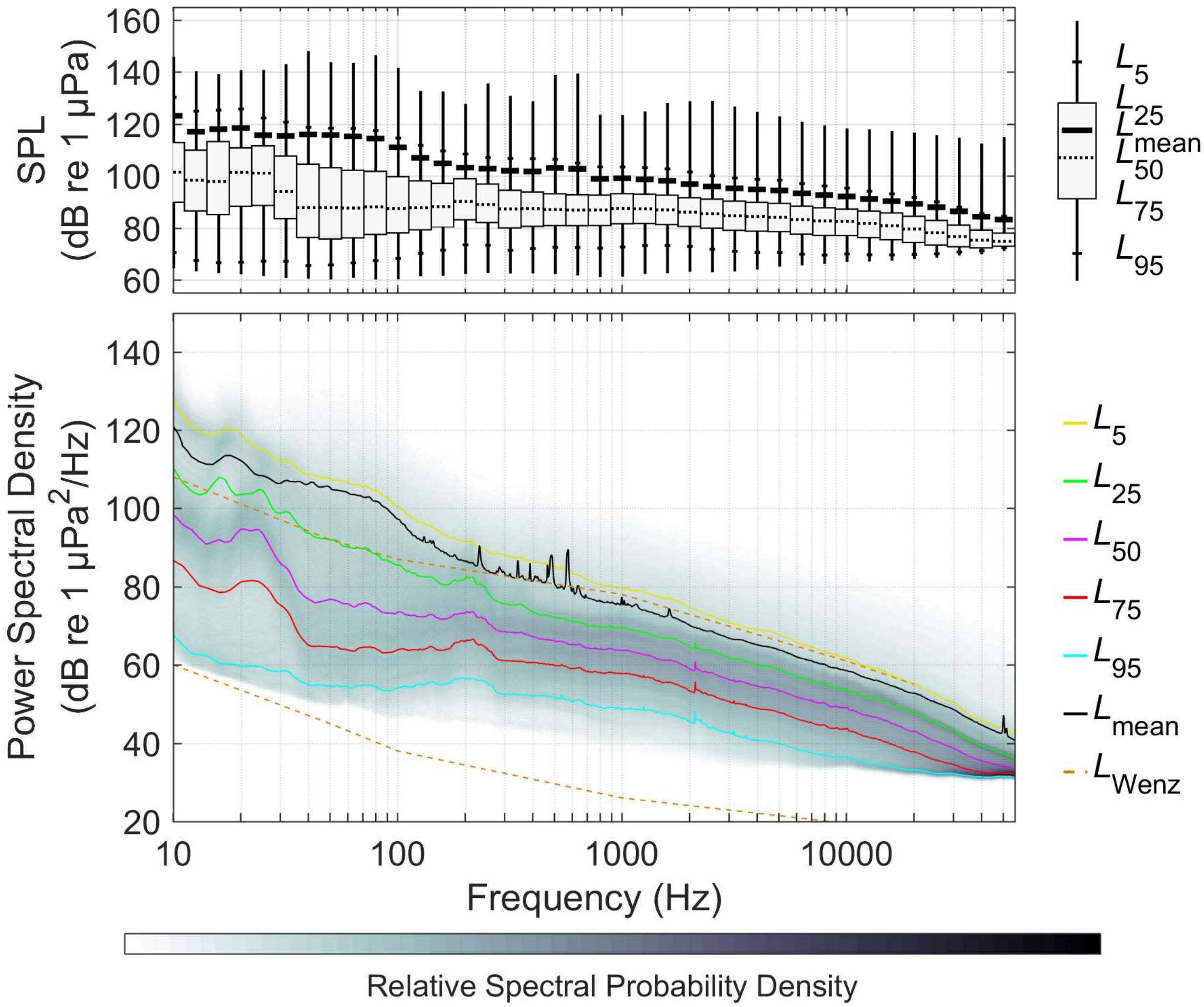
A.4.1. Ambient Sound Pressure Level versus Time

Broadband, decade band SPL versus time and spectrogram through the analysis period (1-hour resolution).



A.4.2. Spectral Levels and 1/3-Octave Band Levels

The top panel shows percentiles and mean 1/3-octave-band SPL (1 minute) over the analysis period. The bottom panel shows percentiles and mean power spectral density levels over the same time period.



A.4.3. Table of Broadband and 1/3-Octave SPL Values

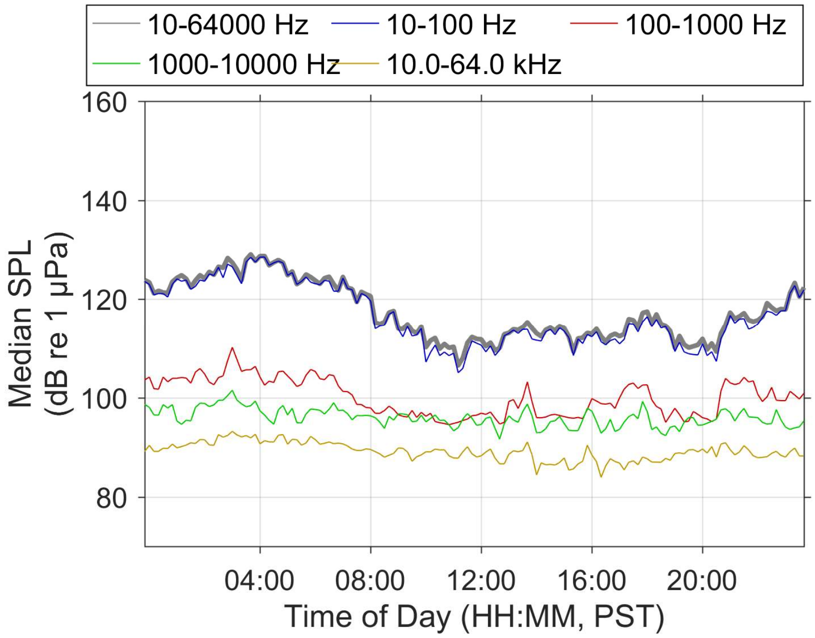
Broadband and 1/3-octave-band sound levels (dB re 1 µPa) for the 95th, 75th, 50th, 25th, and 5th exceedance percentiles. Third-octave-bands are listed by centre frequency. Levels correspond to 1-minute SPLs.

Band centre frequency (Hz)	L_{95}	L_{75}	L_{50}	L_{25}	L_5
Broadband	92.5	105.3	115.9	125.3	135.9
10	70.47	89.86	101.43	112.82	130.3
12.6	67.42	86.51	98.34	109.92	124.98
15.8	66.58	85.09	97.86	113.23	125.3
20	66.71	88.29	101.36	110.8	125.78
25.1	67.16	88.6	101.09	111.59	122.33
31.6	67.14	83.53	94.05	107.67	120.72
39.8	65.44	76.28	87.79	104.51	118.74
50.1	65.65	75.71	87.79	103.14	118.33
63.1	66.52	76.12	87.61	102.18	118.24
79.4	67.36	77.43	88.07	101.76	117.51
100	68.2	78.01	87.47	99.69	114.58
125.9	70.22	79.23	87.72	98.09	111.74
158.5	71.38	80.19	88.17	97.15	109.63
199.5	73.44	83.1	90.16	98.91	108.45
251.2	73.3	82.01	88.96	96.84	107.08
316.2	71.34	79.94	87.28	94.46	106.71
398.1	72.05	80.56	87.41	93.81	106.63
501.2	72.51	80.85	87.04	93.11	106.42
631	72.43	80.82	86.84	92.69	105

Band centre frequency (Hz)	L_{95}	L_{75}	L_{50}	L_{25}	L_5
794.3	72.18	80.87	86.88	92.6	103.48
1000	72.64	81.57	87.48	93.15	103.42
1258.9	73.18	81.64	87.33	92.95	103.19
1584.9	73.18	81.25	86.89	92.58	102.71
1995.3	72.8	80.53	86.04	91.59	101.51
2511.9	71.75	79.85	85.42	91.06	100.04
3162.3	70.93	79.03	84.66	90.27	99.17
3981.1	70.52	78.69	84.33	89.81	98.71
5011.9	70.52	78.52	84.08	89.41	98.32
6309.6	69.81	77.57	83.17	88.34	97.03
7943.3	69.53	77.05	82.66	87.69	96.11
10000	69.92	77.01	82.47	87.19	95.3
12589.3	69.59	76.23	81.68	86.46	94.1
15848.9	69.55	75.42	80.8	85.74	93.07
19952.6	69.7	74.35	79.53	84.44	91.67
25118.9	70	73.35	78.1	82.84	90
31622.8	70.69	72.7	76.66	81.03	87.93
39810.7	71.17	72.28	75.24	79.11	85.46
50118.7	72.34	72.91	74.78	77.95	84.43

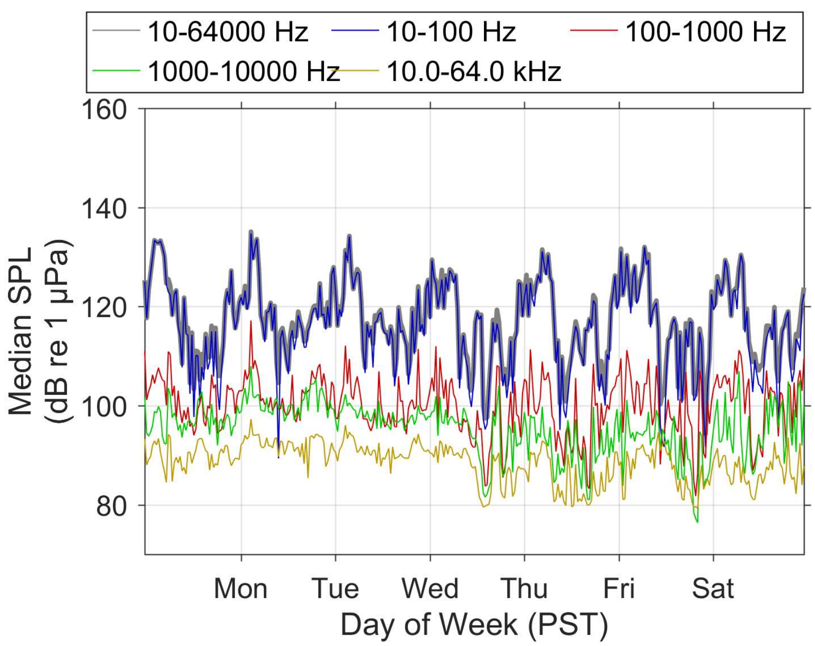
A.4.4. Daily Rhythm Plot

The median 1-minute SPL versus time of day (10-minute resolution) over the analysis period.



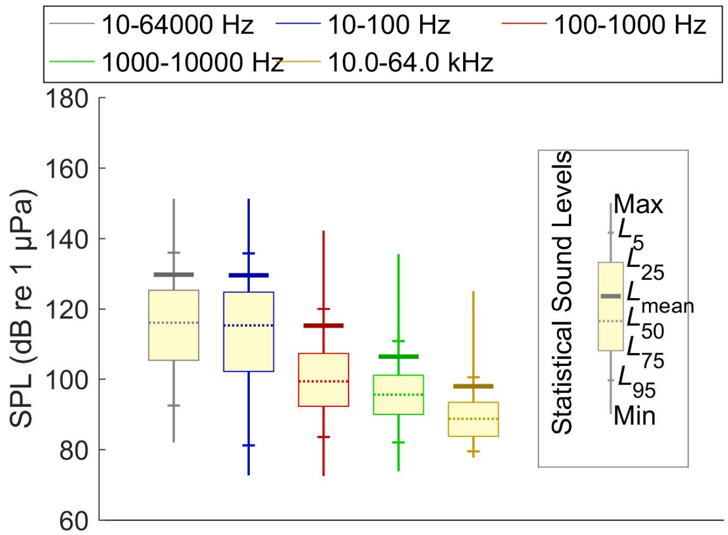
A.4.5. Weekly Rhythm Plot

The median 1-minute SPL versus day of week (30-minute resolution) over the analysis period.



A.4.6. SPL Box Plot

The broadband and decade-band sound pressure level (1 minute) statistics over the analysis period.



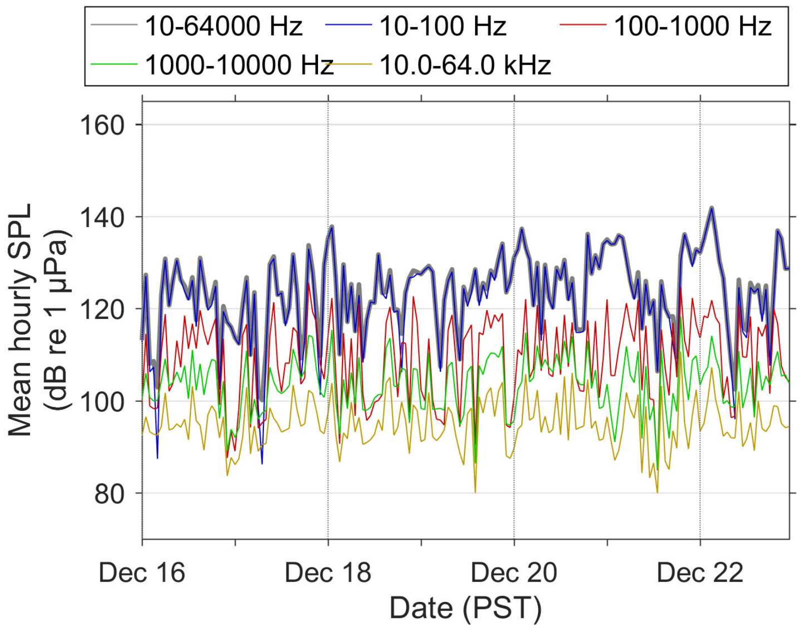
A.4.7. Table of Values

Sound pressure level (1 minute) statistics (dB re 1 μPa) used to generate the SPL box plot in Section A.4.6.

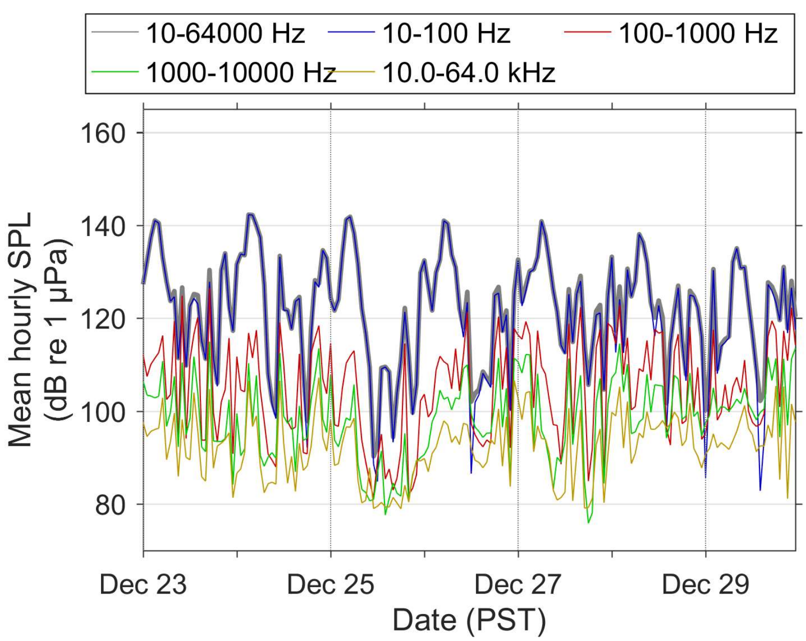
Sound Level Statistic	10-64000 Hz	10-100 Hz	100-1000 Hz	1000-10000 Hz	10.0-64.0 kHz
Min	82	72.7	72.4	73.8	77.7
L95	92.5	81.1	83.5	82	79.5
L75	105.3	102.1	92.2	89.9	83.7
L50	115.9	115.2	99.3	95.5	88.7
L25	125.3	124.7	107.2	101	93.4
L05	135.9	135.7	120	110.7	100.5
Max	151.2	151.2	142.2	135.5	125
Mean	129.7	129.5	115.1	106.3	97.9

A.4.8. Weekly Band Levels

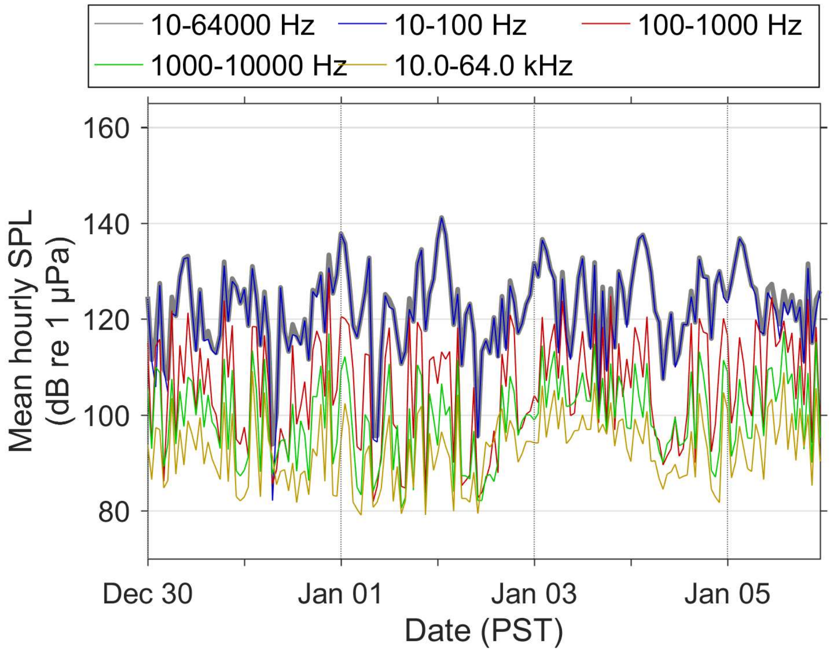
A.4.8.1. Sun 16 Dec to Sun 23 Dec 2018



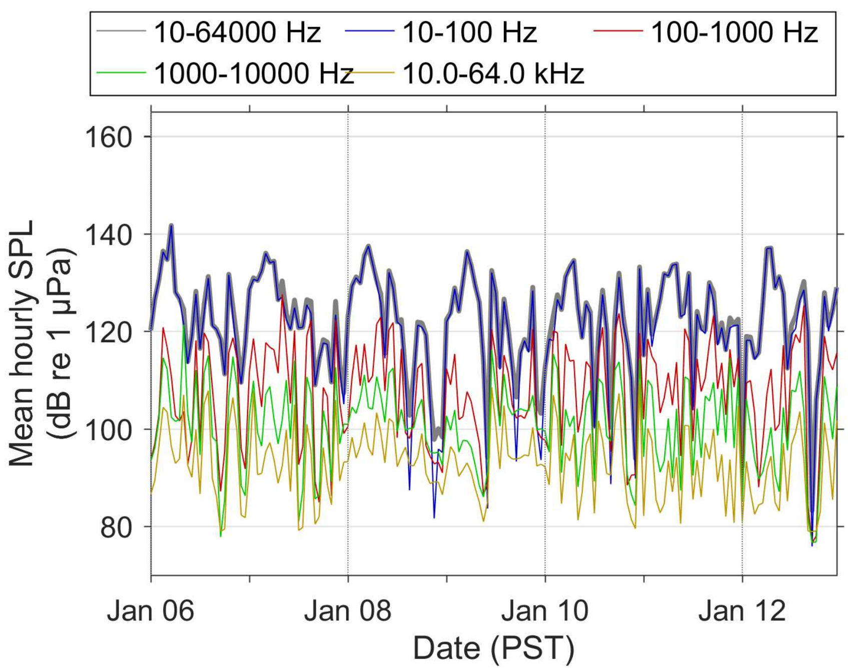
A.4.8.2. Sun 23 Dec to Sun 30 Dec 2018



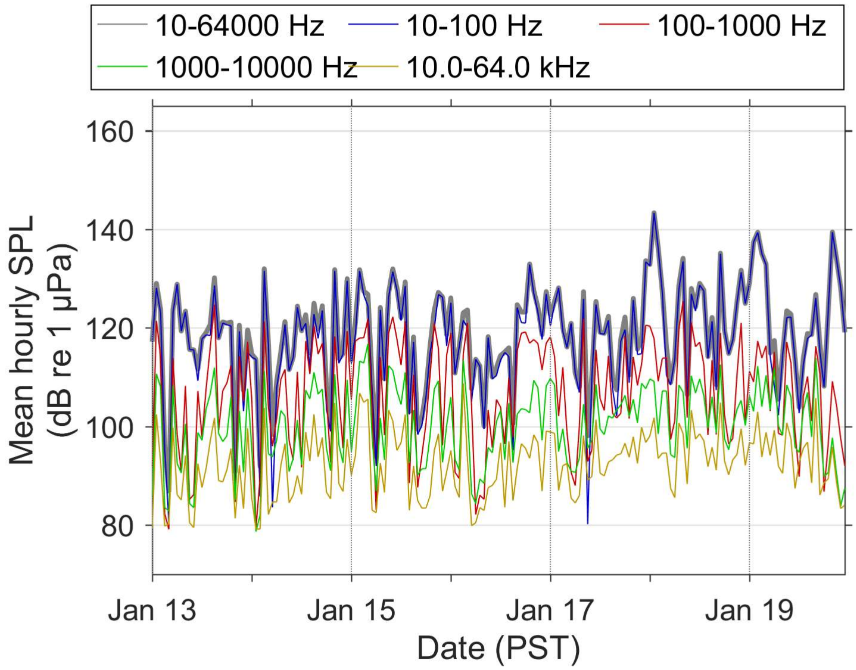
A.4.8.3. Sun 30 Dec 2018 to Sun 6 Jan 2019



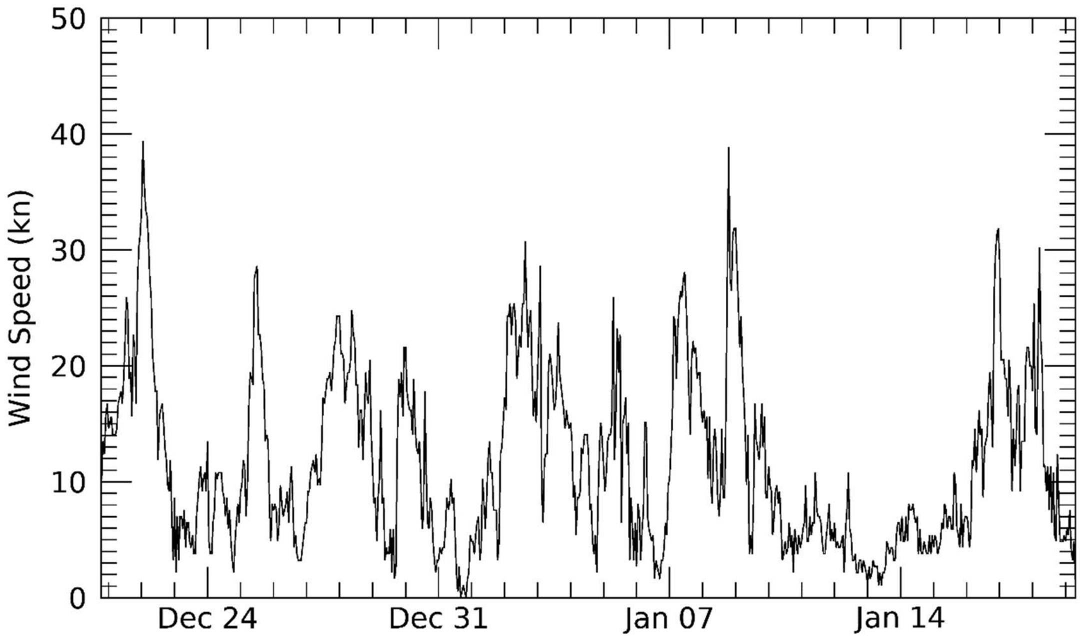
A.4.8.4. Sun 6 Jan to Sun 13 Jan



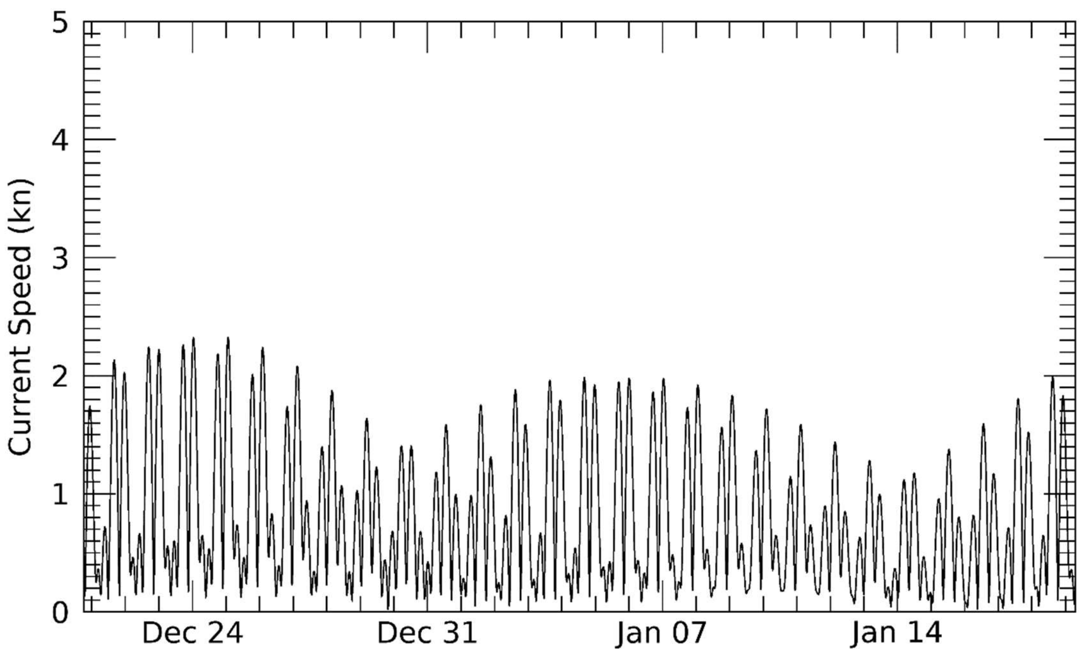
A.4.8.5. Sun Jan 13 to Sun Jan 20



A.4.9. Hourly Wind Speed



A.4.10. Near-seafloor Current Speed



Appendix B. Example Marine Mammal Detection Report for 1 Month

B.1. Introduction

JASCO Applied Sciences was contracted to the Vancouver Fraser Port Authority (VFPA) to analyze underwater sound in Boundary Pass as part of VFPA's Enhancing Cetacean Habitat and Observations (ECHO) program. Acoustic data were collected using JASCO's Autonomous Multichannel Acoustic Recorders (AMARs) starting 12 Dec 2018. This report contains analysis of data collected from the beginning of the recording period until 16 Jun 2019[3].

The acoustic data were processed to detect marine mammal vocalizations. This report presents the results in the following three formats:

- Pie charts of the relative number of automatic vocalizations detections by species. The automated detector was used to detect the vocalizations of killer whales (*Orcinus orca*), humpback whales (*Megaptera novaeangliae*), and Pacific white-sided dolphins (*Lagenorhynchus obliquidens*).
- Graphs showing the number of detections for each hour and per day for each species. All graphs are in Pacific Standard Time unless otherwise indicated.
- Spectrograms showing how animal-vocalization frequencies varied in time.

B.2. Methods

B.2.1. Acoustic Data

Acoustic data were collected in Boundary Pass using JASCO's AMARs. Table 7 lists the deployment coordinates and recording start/end times. The recorders were deployed within 180 m of each other.

Table 7. AMAR recorder locations and periods used for analysis. Two AMARs recorded simultaneously during a small fraction of the recording period. During these times, if the same vocalization was detected on two AMARs, it was only counted and displayed once in the results section.

AMAR S/N	Latitude (N)	Longitude (W)	Water Depth (m)	Start Date/Time	End Date/Time
437	48° 45.60665'	123° 3.86085'	197	2018-12-12 22:32	2019-02-07 16:42
436	48° 45.63044'	123° 3.79622'	199	2019-01-23 00:00	2019-03-20 18:21
418	48° 45.63369'	123° 3.77304'	197	2019-03-21 14:24	2019-05-17 07:31
419	48° 45.67526'	123° 3.74762'	196	2019-05-08 00:00	2019-07-03 18:03

B.2.2. Detection Algorithm

An automated detector developed by JASCO was used to detect the vocalizations of killer whales, humpback whales, Pacific white-side dolphins, and fish sounds from acoustic recordings. The algorithm employed was similar to the one described in Moloney et al. (2014) and Dewey et al. (2015). Figure 31 shows the various processing steps of the detector.

[3] This report has been truncated for this appendix to only show one synodic month of results.

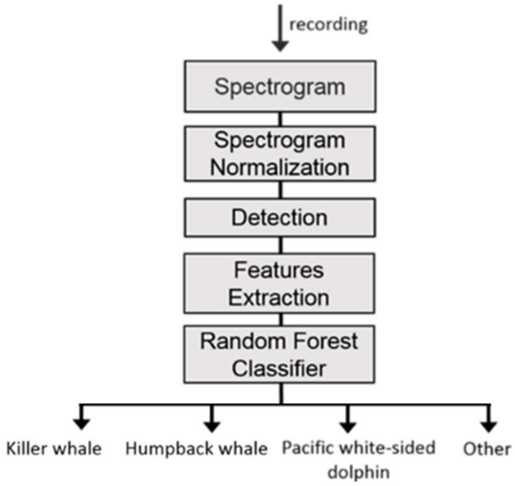


Figure 31. The process for automatic detections of killer whales, humpback whales, Pacific white-side dolphins, and fish sounds.

The algorithm first calculated the spectrogram and normalized it for each frequency band. Next, the spectrogram was segmented to detect acoustic events between 10 Hz and 8 kHz. For each event, a set of 40 features representing salient characteristics of the spectrogram were extracted, several of which were calculated following Fristrup and Watkins (1993) and Mellinger and Bradbury (2007). The features were based on the spectrogram, frequency envelope, and amplitude envelope of the signal.

Extracted features were presented to a classifier to determine the class of the sound detected. The classification was performed using a random forest classifier (Breiman 2001), which was trained using several thousands of manually annotated vocalizations in recordings collected at different locations in British Columbia (Mouy et al. 2015). The random forest was defined with the following classes: “killer whale”, “humpback whale”, “Pacific white-side dolphin”, “fish”, and “other”. Figure 32 illustrates the key processing steps of the detector on a recording that contained killer whale vocalizations.

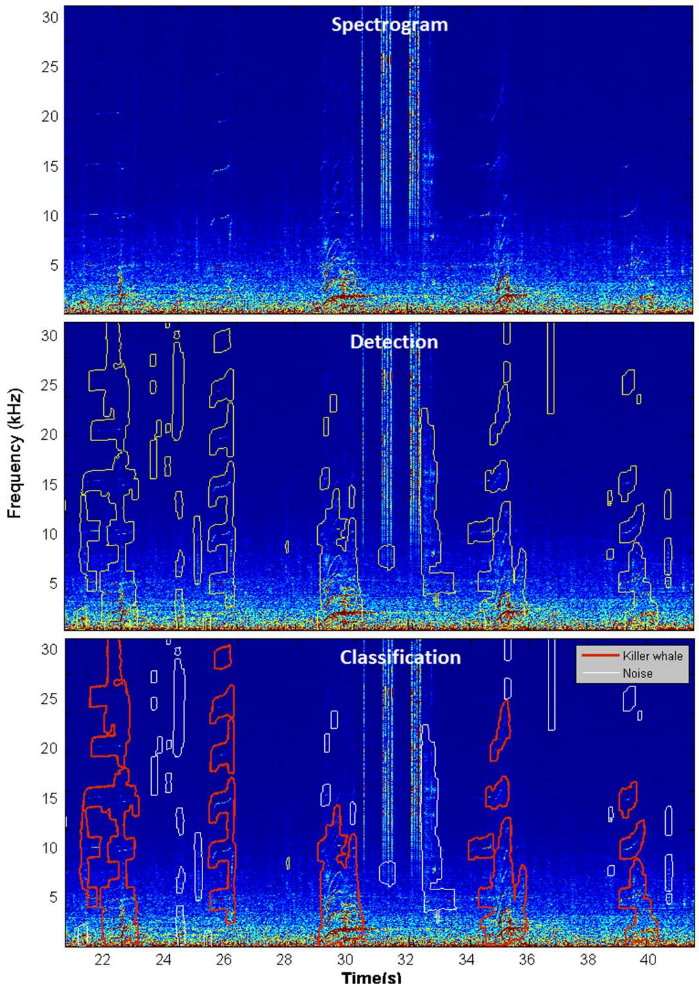


Figure 32. Key processing steps of the detector. Top panel: Spectrogram with killer whale vocalizations. Middle panel: Acoustic events detected in the spectrogram. Bottom panel: Killer whale vocalizations classified using a random forest classifier.

All automated detections from killer whale, humpback whale, and Pacific white-sided dolphin vocalizations were manually verified by an experienced analyst using JASCO's software PAMLab. All false detections for these species were excluded from the graphs in this report.

The automated detector identified 331,347 potential fish sounds throughout the entire recording period. There were too many detections to review all of them manually, so an experienced analyst reviewed a selection of detections using PAMLab. No true fish sounds were identified by the analyst so results for fish detections are not included in this report.

B.3. Results: 20 Dec 2018 to 19 Jan 2019

B.3.1. Relative Vocalization Detections by Species

A total of 1090 killer whale vocalizations and 157 humpback whale vocalizations were reported by the automated detector at AMAR 437 from 20 Dec 2018 to 19 Jan 2019. No Pacific white-sided dolphin vocalizations were detected at AMAR 437 during this period. Figure 33 shows the proportion of detections by species for this period.

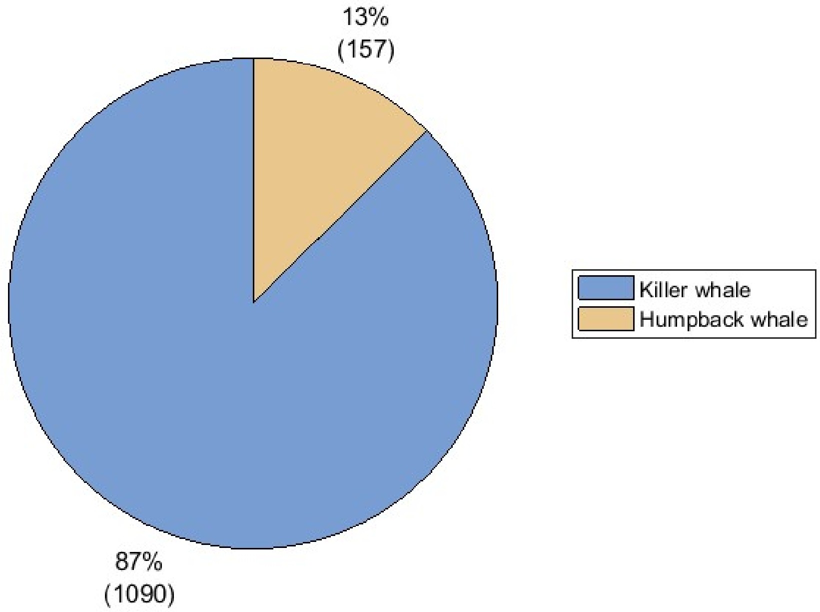


Figure 33. Relative vocalization detections at AMAR 437 from 20 Dec 2018 to 19 Jan 2019.

B.3.2. Killer whales

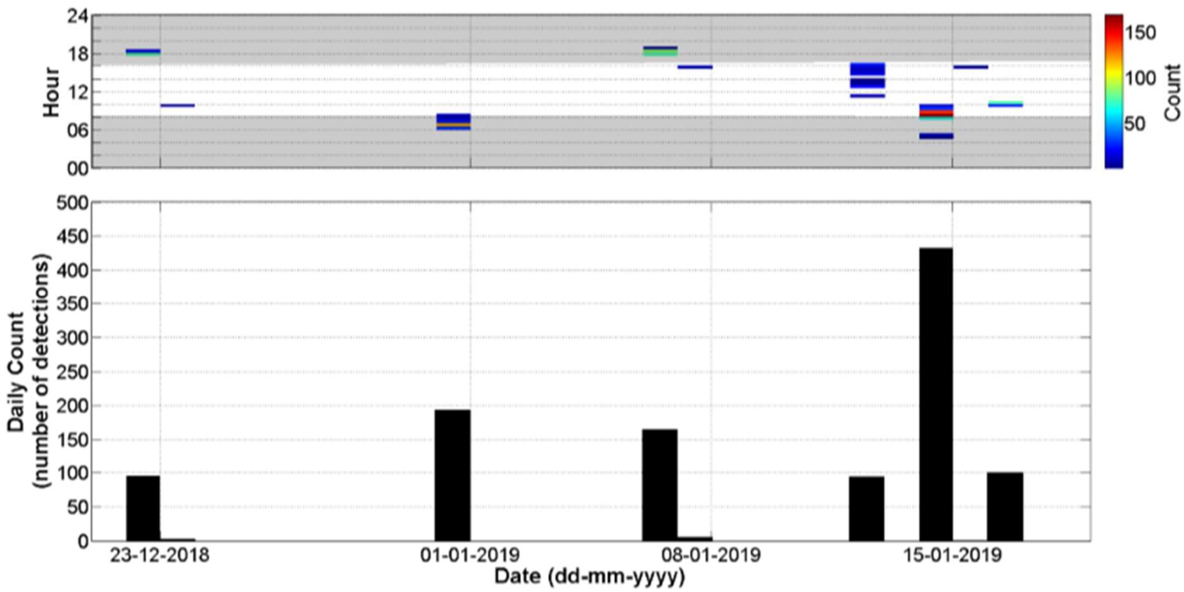


Figure 34. Hourly and daily detection counts (PST) of killer whale vocalizations at AMAR 437 from 20 Dec 2018 to 19 Jan 2019. Grey areas indicate darkness period.

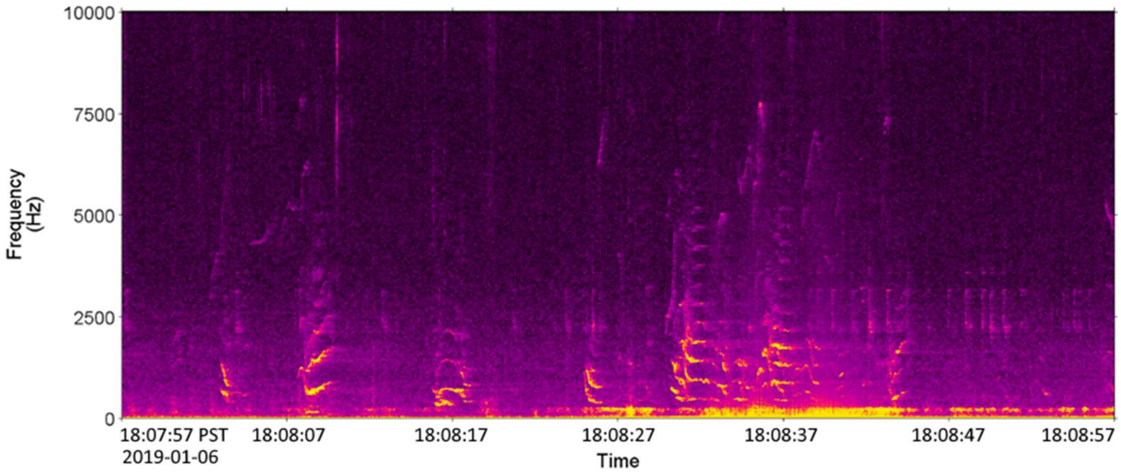


Figure 35. Spectrogram of killer whale vocalizations at AMAR 437 on 6 Jan 2019.

B.3.3. Humpback whales

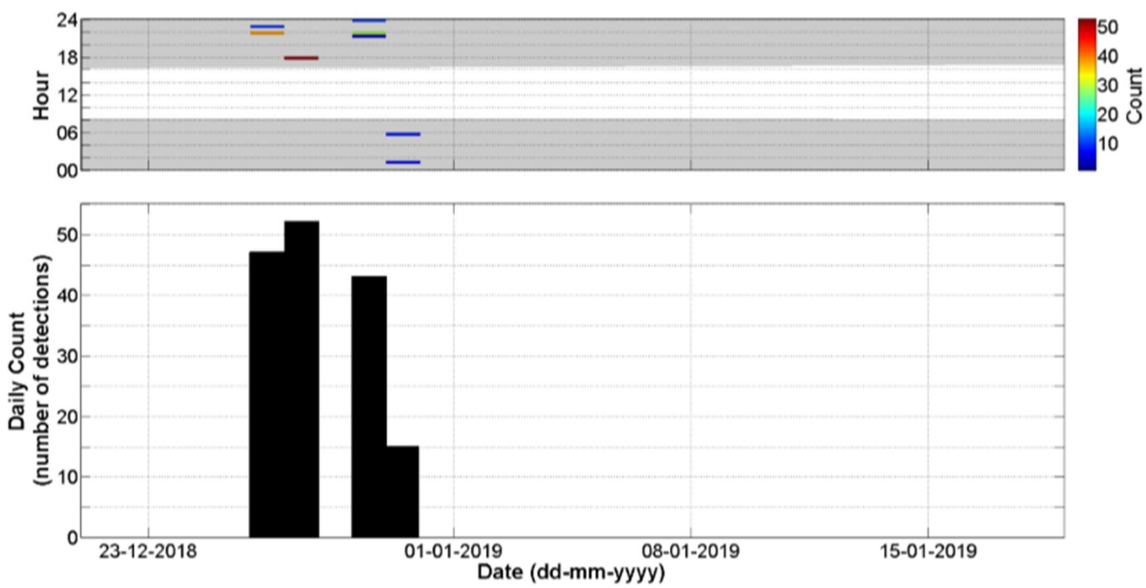


Figure 36. Hourly and daily detection counts (PST) of humpback whale vocalizations at AMAR 437 from 20 Dec 2018 to 19 Jan 2019. Grey areas indicate darkness period.

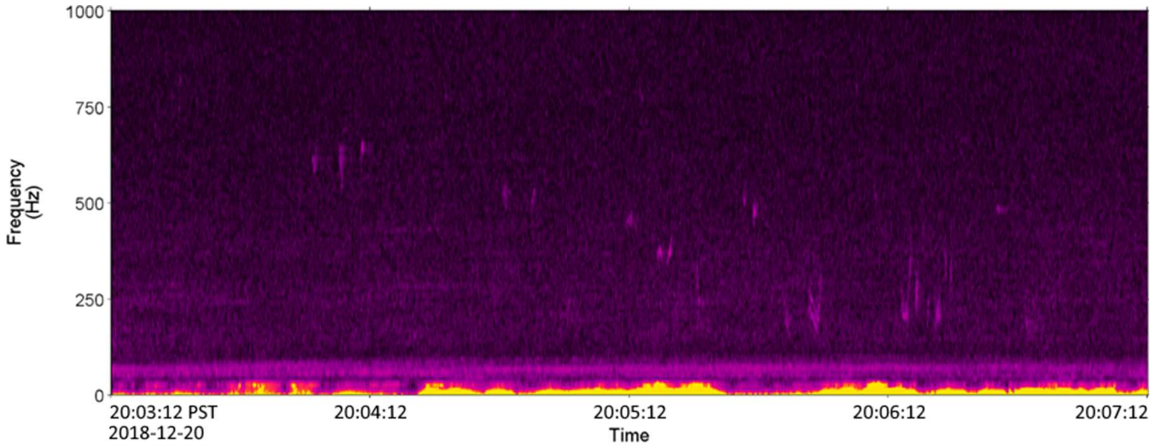


Figure 37. Spectrogram of humpback whale vocalizations at AMAR 437 on 20 Dec 2018.

B.3.4. Pacific white-sided dolphins

No Pacific white-sided dolphins were detected on AMAR 437 recordings during the analysis period.

Appendix C. Vessel Source Level Calculations using ShipSound

JASCO's ShipSound software monitors sound level measurements and AIS broadcasts from passing vessels. It identifies vessels that traverse a predefined transit area and then automatically extracts the corresponding acoustic data for analysis. It uses a vessel's broadcast speed together with a cepstral analysis of the Lloyd mirror pattern to determine the timing and location of closest point of approach (CPA) of the vessel's acoustic centre. ShipSound can analyze streaming data from a hydrophone in real time or, as in the case of the Boundary Pass autonomous listening stations, can analyze archival hydrophone data downloaded from autonomous recorders.

The ANSI/ASA S12.64 data window is defined by the period over which the acoustic centre is within ±30° of the CPA. ShipSound automatically determines the data window and processes a single acoustic channel in 1-second periods stepped in 0.5-second intervals (Figure C-1). Spectrum measurements are calculated using 1-second fast Fourier transforms, shaded using a Hanning window.

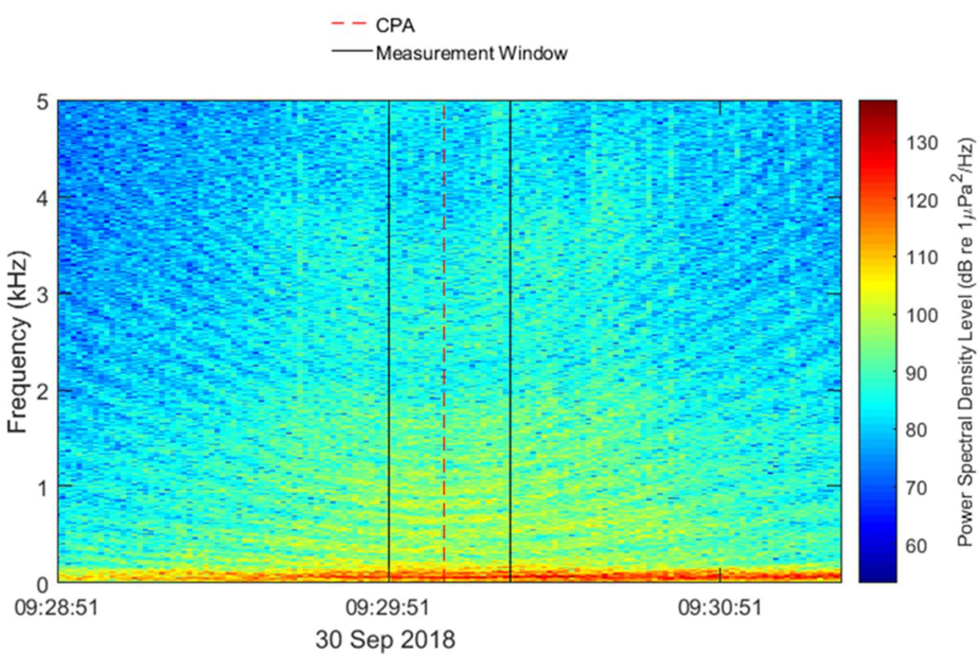


Figure C-1. Spectrogram of a single vessel measurement from ShipSound, showing the closest point of approach (CPA) time (dashed red line) and the measurement window (black box) used for calculating vessel source levels. The spectrogram shows the spectrum of the underwater sound pressure recorded on the AMAR versus time and frequency. Although acoustic data were characterized up to 64 kHz, the spectrogram is shown up to 5 kHz because the Lloyd mirror pattern is strongest at lower frequencies.

ShipSound calculates two metrics representing vessel noise emissions: Radiated Noise Level (RNL) and Monopole Source Level (MSL). RNL is equal to the measured sound pressure level, back-propagated according to the distance between a source and the hydrophone. The software applies the ANSI/ASA S12.64 Grade-A method for back-propagation distance: it determines instantaneous vessel range (R) in metres from the measurement hydrophone for each 1-second step within the data window. The RNL back propagation method of $20 \times \mathrm{Log}_{10}(R)$ is applied to the spectra of each step separately. MSL is equal to the measured sound pressure level scaled according to a numerical acoustic transmission loss (TL) model that accounts for the effect of the local environment on sound propagation (i.e., sea-surface reflection, water column refraction and absorption, and bottom loss). MSL back-propagation is performed using predictions of the Parabolic Equation model RAM, modified to treat shear wave reflection losses, in decidecade-bands to 5 kHz, and an image reflectivity model at higher frequencies. MSL back-propagation requires a source depth, which is defined in ShipSound as a Gaussian distribution centred at the shaft depth minus 0.7 of the propeller radius, when that information is available, or half the vessel draft otherwise. RNL is the source level calculation method specified by the ANSI standard whereas most acoustic models used for assessing shipping noise effects on marine fauna use MSL.

Environmental conditions (wind speed and current speed) were also recorded for each measurement. Meteorological data for Boundary Pass were obtained from Environment Canada weather stations as described in Section 2.1.4. Ocean current measurements were obtained from ADCP measurements, or, when unavailable, the WebTide Tidal Prediction Model (v 0.7.1) as described in Section 2.1.2. Ocean current data were used to calculate speed through water from speed over ground (SOG) information received via AIS for each vessel measurement.

PortListen includes a web-based user interface for accessing vessel and measurement information. A table view screen lets the user select and view multiple measurements by vessel criteria. This information, including broadband MSL and RNL source levels, can be exported as a spreadsheet. Vessel measurements are summarized in PDFs, presenting vessel and environment information, and the decidecade-band MSL and RNL source levels.

All source level measurements were subjected to two phases of quality control: an automated review of source and background levels that was performed on a decidecade-band basis, and a manual review of the overall measurement. For the first quality review phase, ShipSound calculated background noise in each frequency band from one-minute time periods before and after the vessel entered the measurement funnel. ShipSound accepted band source levels if they exceeded background levels by more than 10 dB, corrected them if they exceeded background levels by 3–10 dB, and rejected them if they were less than 3 dB above background. Adjusted and rejected levels were flagged in the database. Figure C-2 summarizes this approach. The overall vessel measurement was not necessarily rejected if some of the decidecade-band source levels were rejected during the automated quality review phase.

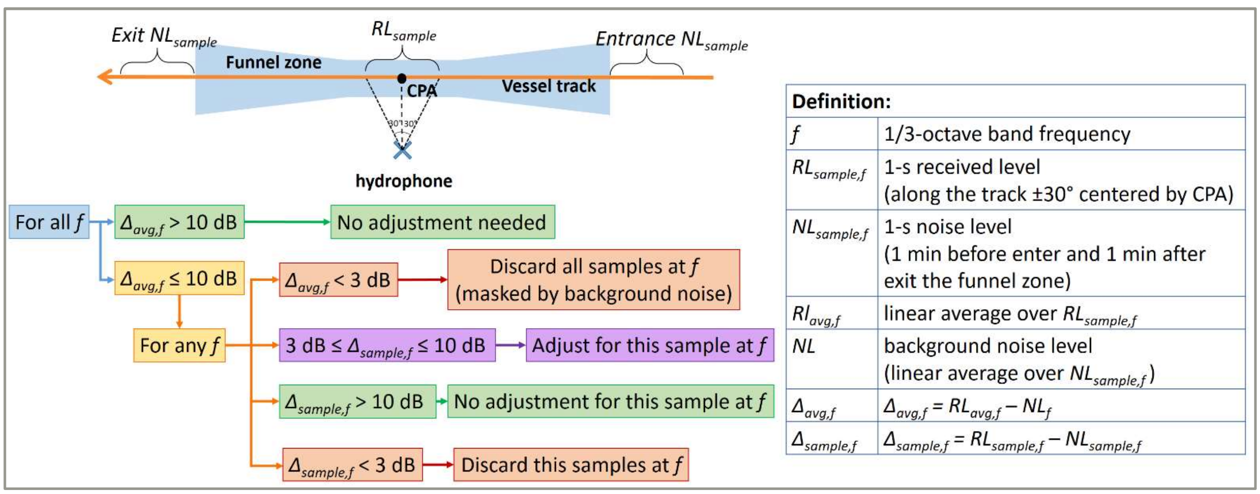


Figure C-2. Background noise comparison and adjustment process as part of the first (automated) phase of quality control.

For the second quality review phase, an experienced analyst used the web-based interface to manually review every measurement. An analyst could reject a measurement because it contained interference from other vessels, had high levels of background noise (i.e., a large number of rejected band source levels), or if a vessel did not have constant speed and a straight track inside the data window.

Appendix D. Comparison of Sound Levels between Simultaneously Recording AMARs

The following sections compare the distributions of decidecade-band sound levels between two simultaneously recording AMARs for periods of data overlap during each deployment. These figures support the analysis presented in Section 3.1.5.

D.1. Deployment 1

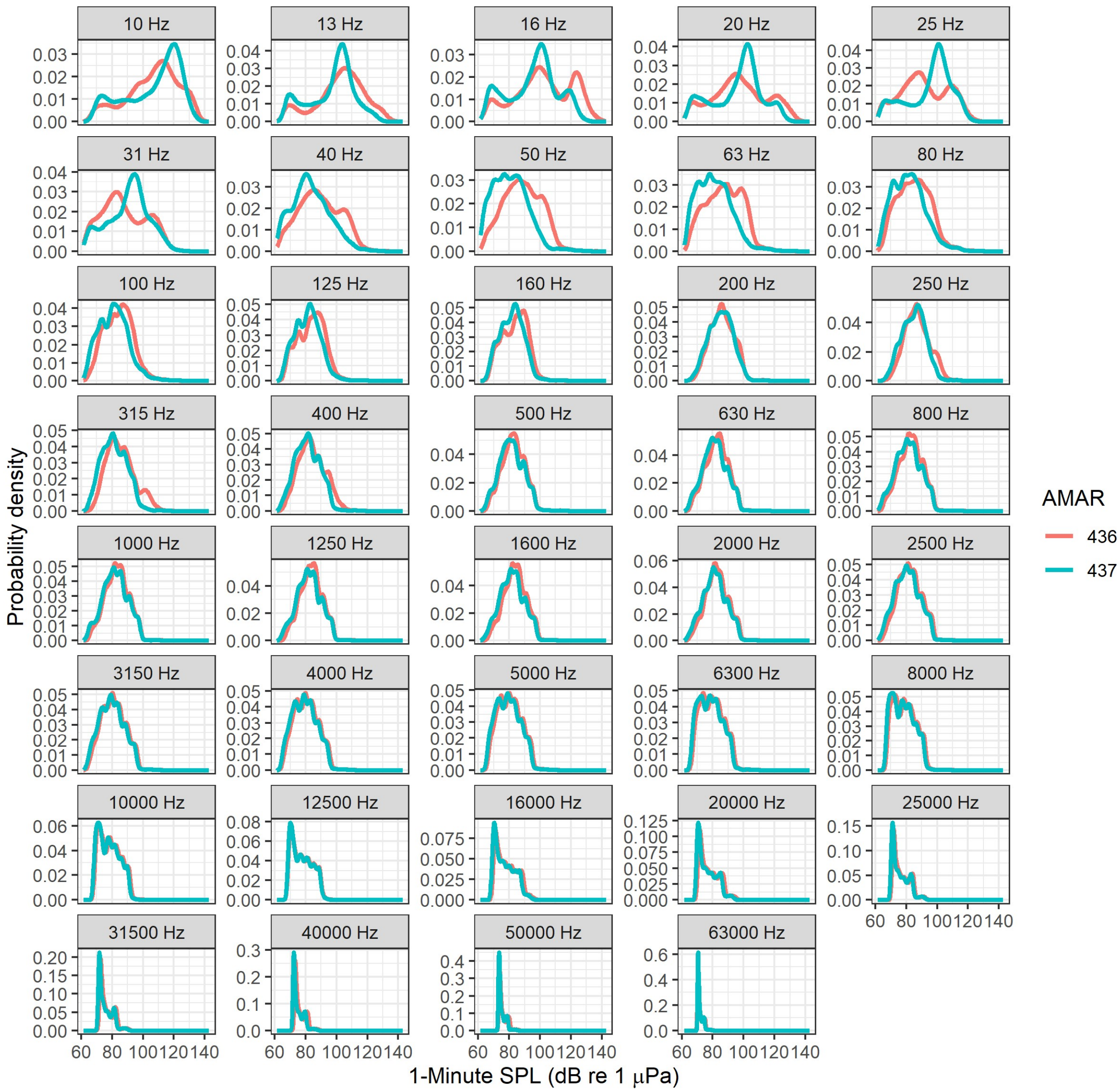


Figure D-1. *Comparing sound level distributions during periods without vessels, Deployment 1:* Decidecade band sound level distributions, during AIS vessel absence, measured by simultaneously recording AMARs during Deployment 1 (10324 minutes). Data were pre-filtered to exclude minutes when AIS vessels were within 6 km of the hydrophones and/or when current speeds were greater than 0.5 m/s. Panel headings indicate the centre frequency of the decidecade band. Note that this figure is identical to Figure 22.

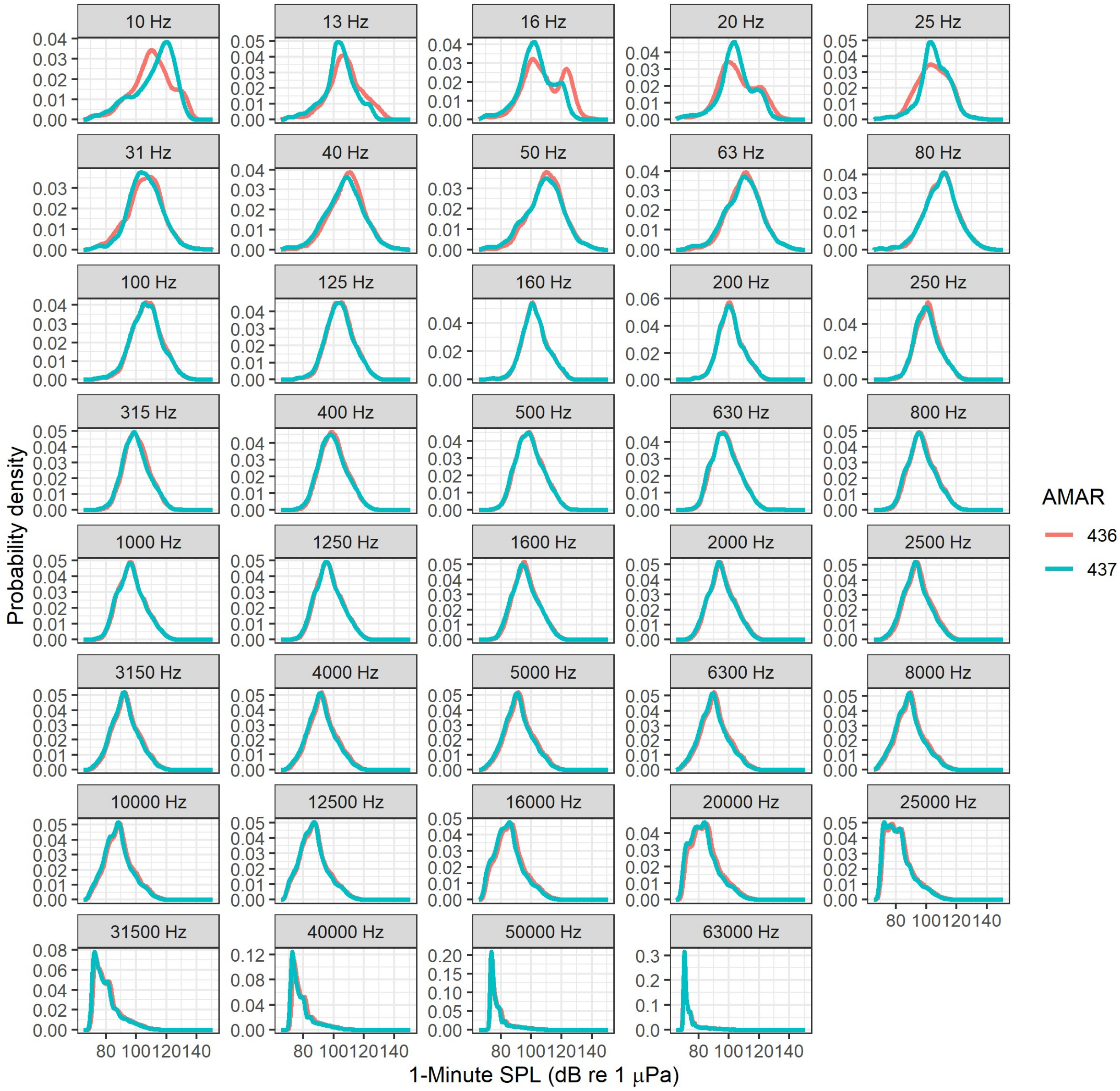


Figure D-2. *Comparing sound level distributions during periods with vessels, Deployment 1:* Decidecade band sound level distributions when AIS-broadcasting vessels were within 6 km of the hydrophones, as measured by simultaneously recording AMARs during Deployment 1 (4003 minutes). Data were pre-filtered to exclude minutes when current speeds were greater than 0.5 m/s. Panel headings indicate the centre frequency of the decidecade band. Note that this figure is identical to Figure 23.

D.2. Deployment 2

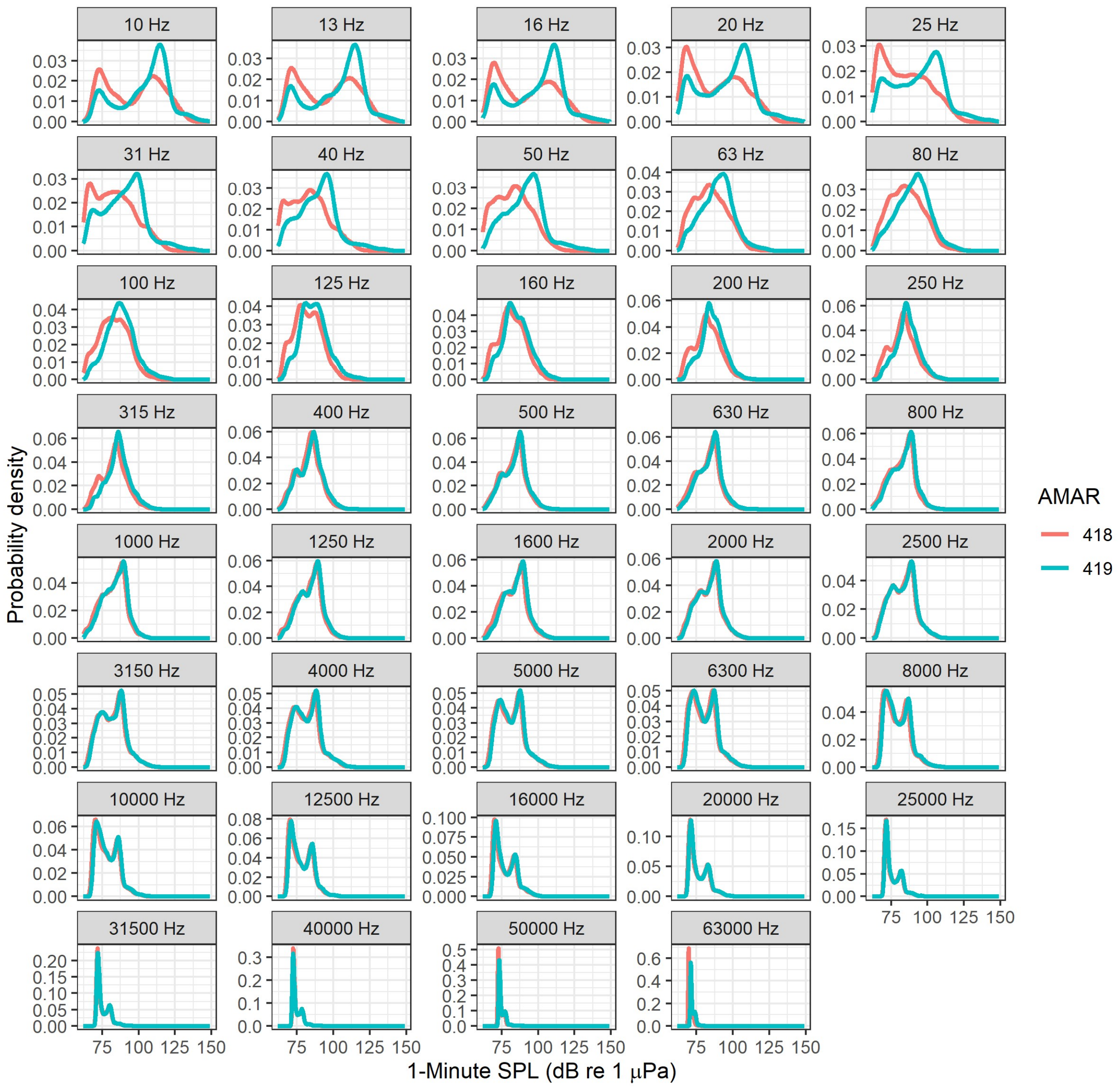


Figure D-3. *Comparing sound level distributions during periods without vessels, Deployment 2:* Decidecade band sound level distributions, during AIS vessel absence, measured by simultaneously recording AMARs during Deployment 2 (5929 minutes). Data were pre-filtered to exclude minutes when AIS vessels were within 6 km of the hydrophones and/or when current speeds were greater than 0.5 m/s. Panel headings indicate the centre frequency of the decidecade band.

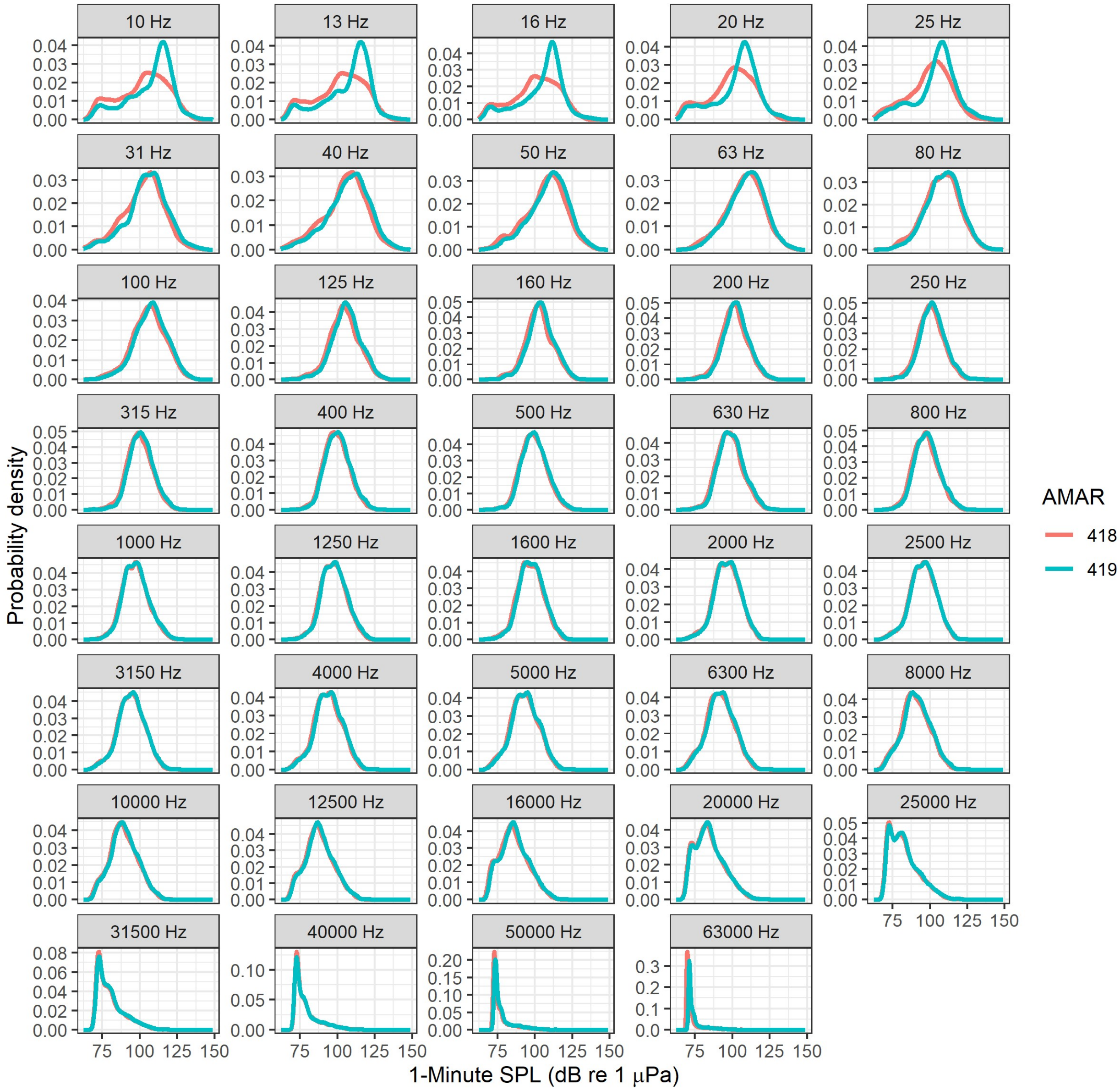


Figure D-4. *Comparing sound level distributions during periods with vessels, Deployment 2:* Decidecade band sound level distributions when AIS-broadcasting vessels were within 6 km of the hydrophones, as measured by simultaneously recording AMARs during Deployment 2 (3180 minutes). Data were pre-filtered to exclude minutes when current speeds were greater than 0.5 m/s. Panel headings indicate the centre frequency of the decidecade band.

D.3. Deployment 3

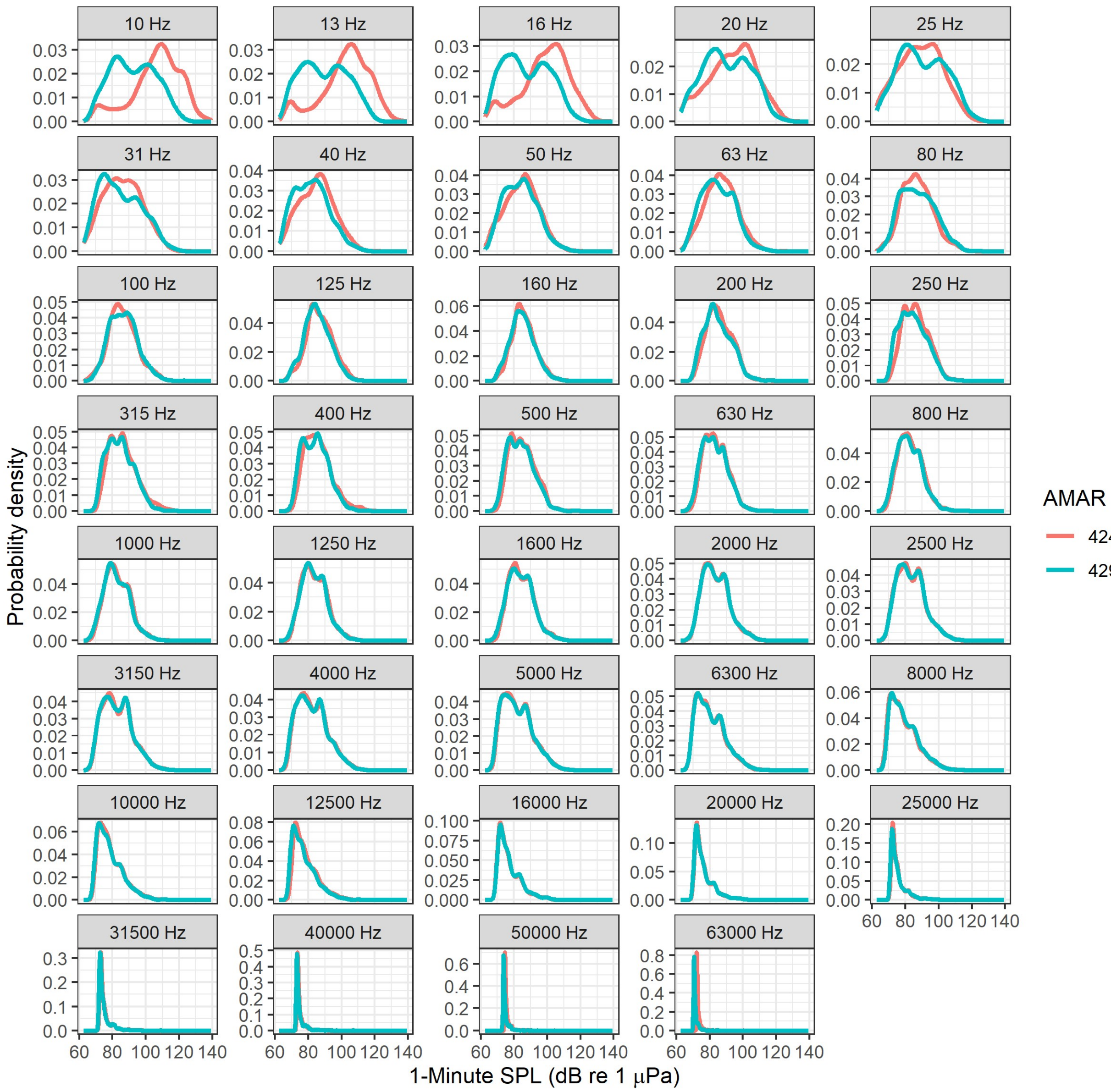


Figure D-5. *Comparing sound level distributions during periods without vessels, Deployment 3:* Decidecade band sound level distributions, during AIS vessel absence, measured by simultaneously recording AMARs during Deployment 3 (1928 minutes). Data were pre-filtered to exclude minutes when AIS vessels were within 6 km of the hydrophones and/or when current speeds were greater than 0.5 m/s. Panel headings indicate the centre frequency of the decidecade band.

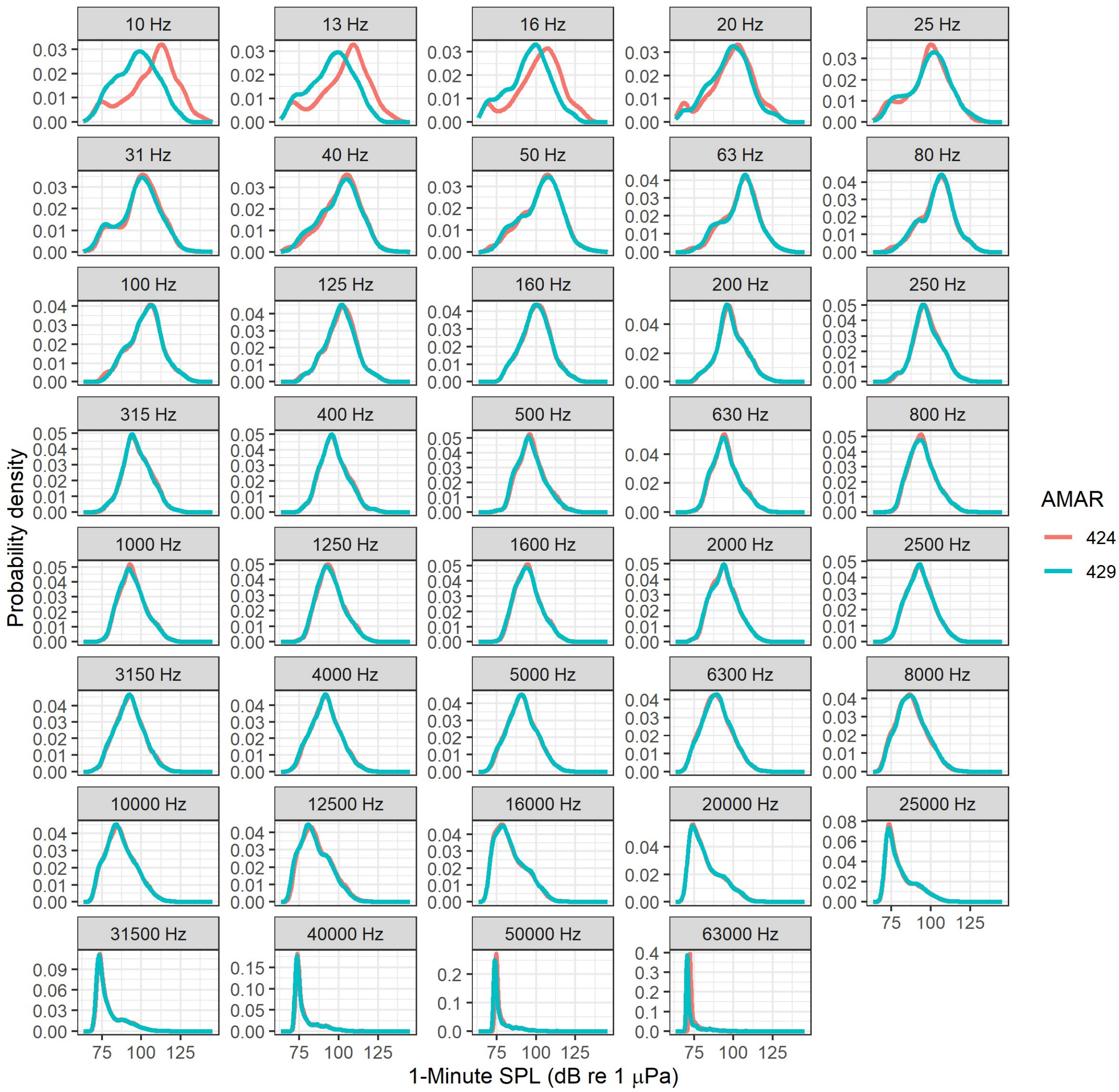


Figure D-6. *Comparing sound level distributions during periods with vessels, Deployment 3:* Decidecade band sound level distributions when AIS-broadcasting vessels were within 6 km of the hydrophones, as measured by simultaneously recording AMARs during Deployment 3 (1441 minutes). Data were pre-filtered to exclude minutes when current speeds were greater than 0.5 m/s. Panel headings indicate the centre frequency of the decidecade band.

Appendix E. Summary of Vessel Source Level Measurements

Table E-1 lists the total number of accepted vessel source level measurements during the analysis period. Table E-2 lists the vessel acceptance rate as a percentage.

Table E-1. Number of accepted vessel source level measurements during Year 1 (Deployments 1–3, Dec 2018 to Oct 2019). The number of measurements are lower for the first and last months (Dec 2018 and Oct 2019) because data were acquired for approximately half of those months

Vessel Category	Dec-18	Jan-19	Feb-19	Mar-19	Apr-19	May-19	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Total
Bulker	112	249	194	210	190	234	180	172	182	204	75	**2002**
Container Ship	51	117	103	94	94	116	93	100	107	91	52	**1018**
Cruise	0	0	0	1	5	23	6	13	5	22	9	**84**
Dredger	0	0	0	2	0	0	0	0	0	0	0	**2**
Ferry	1	2	0	0	8	18	3	0	0	0	0	**32**
Fishing Vessel	0	1	1	4	7	15	6	1	1	0	0	**36**
Government/Research	0	5	1	3	3	3	3	0	1	3	3	**25**
High Speed Ferry	0	0	0	0	0	1	0	0	0	0	1	**2**
Naval Vessel	0	2	12	7	4	7	3	15	7	3	3	**63**
Other	4	2	3	2	3	3	2	0	6	2	4	**31**
Passenger (<100 m)	0	0	0	0	0	2	0	2	1	2	1	**8**
Recreational	0	0	0	0	1	9	1	6	4	3	0	**24**
Tanker	10	22	9	32	20	21	19	20	15	19	7	**194**
Tug	12	44	34	27	28	44	24	24	24	33	16	**310**
Vehicle Carrier	18	34	41	38	38	44	28	38	34	30	20	**363**

Table E-2. Acceptance rate (percent) of vessel source level measurements during Year 1 (Deployments 1–3, Dec 2018 to Oct 2019). Cells with “NA” indicate there were no accepted or rejected measurements for the corresponding month and vessel category.

Vessel Category	Dec-18	Jan-19	Feb-19	Mar-19	Apr-19	May-19	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Average
Bulker	79	73	78	76	80	68	68	70	68	71	74	**73**
Container Ship	75	72	87	80	81	78	73	78	81	71	80	**78**
Cruise	NA	NA	NA	50	63	72	50	72	56	63	60	**64**
Dredger	NA	NA	0	100	NA	NA	NA	NA	NA	NA	NA	**67**
Ferry	100	100	NA	NA	89	86	50	NA	NA	NA	NA	**82**
Fishing Vessel	NA	50	33	57	50	79	46	33	100	0	0	**51**
Government/Research	NA	83	33	60	60	38	50	0	20	50	100	**52**
High Speed Ferry	NA	NA	NA	NA	NA	20	0	NA	0	NA	33	**15**
Naval Vessel	NA	25	52	29	36	24	14	38	25	12	43	**29**
Other	80	100	100	100	100	38	25	NA	55	100	80	**63**
Passenger (<100 m)	NA	NA	NA	NA	NA	22	0	29	50	50	100	**26**
Recreational	NA	NA	NA	NA	50	75	13	38	36	75	NA	**45**
Tanker	50	50	50	73	51	55	61	61	50	63	54	**57**
Tug	44	51	57	49	47	54	51	47	44	52	55	**50**
Vehicle Carrier	90	92	79	81	83	81	64	69	74	79	91	**79**